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Heuristic route generation for the Navy Mission Planner

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THESIS

HEURISTIC ROUTE GENERATION FOR THE NAVY MISSION PLANNER

by

Benjamin C. Pearlswig

September 2013

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Navy Mission Planner is a decision support tool for operational planning at the theater level. It takes as input a scenario defined by a list of ships and their (multi-mission) capabilities, a list of missions to be accomplished, their values to a commander, and their locations, and a fixed time horizon, and it produces as output an employment schedule consisting of a route plan and a set of missions to accomplish for each ship on each day in the scenario. It attempts to maximize the total value of missions covered in the scenario by utilizing each ship to the best of its capabilities, while balancing the geographic distribution of missions, the limited capability of the ships, and the limited time horizon. Prior versions used a limited enumeration routine to generate a manageable number of routes for each ship. We develop a heuristic route generator that reduces the runtime and provides better starting routes, improving the overall quality of solutions obtained by Navy Mission Planner.

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HEURISTIC ROUTE GENERATION FOR THE NAVY MISSION PLANNER

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ABSTRACT

Navy Mission Planner is a decision support tool for operational planning at the theater level. It takes as input a scenario defined by a list of ships and their (multi-mission) capabilities, a list of missions to be accomplished, their values to a commander, and their locations, and a fixed time horizon, and it produces as output an employment schedule consisting of a route plan and a set of missions to accomplish for each ship on each day in the scenario. It attempts to maximize the total value of missions covered in the scenario by utilizing each ship to the best of its capabilities, while balancing the geographic distribution of missions, the limited capability of the ships, and the limited time horizon. Prior versions used a limited enumeration routine to generate a manageable number of routes for each ship. We develop a heuristic route generator that reduces the runtime and provides better starting routes, improving the overall quality of solutions obtained by Navy Mission Planner.

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Air Defense
ASW	Anti-Submarine Warfare
CFMCC	Combined Forces Maritime Component Commander
CMCs	Concurrent Mission Capable Sets
COCOM	Combatant Command
CONOPS	Concept of Operations
GAMS	General Algebraic Modeling System
Intel	Intelligence
JFMCC	Joint Force Maritime Component Commander
JP	Joint Publication
MCM	Mine Countermeasures
MHQ	Maritime Headquarters
MIO	Maritime Interception Operations
MOC	Maritime Operations Center
NCC	Naval Component Commander
NMP	Navy Mission Planner
NSFS	Naval Surface Fire Support
NWDC	Navy Warfare Development Command
NWP	Navy Warfare Publication
OPCON	Operational Control
SubIntel	Submarine Intelligence Collection
SUW	Anti-Surface Warfare
TACMEMO	Tactical Memorandum
TACON	Tactical Control
TBMD	Theater Ballistic Missile Defense
VBA	Visual Basic for Applications

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EXECUTIVE SUMMARY

Navy Mission Planner (NMP) is a decision support tool for operational planning at the theater level. The Navy's official process for theater level planning is manual, and the multiple dimensions of planning require a tool that can account for the variables associated with these plans. With advancing technology allowing ships to conduct multiple missions across the spectrum of warfare, a more advance planning tool is required to accommodate the optimal employment of vessels.

This model takes as input a scenario defined by a list of ships and their (multi-mission) capabilities, a list of missions to be accomplished, their values to a commander, and their locations, and a fixed time horizon. This allows for the program to evaluate each mission and each vessel to utilize and allocate the best asset to the correct area and mission. It produces as output an employment schedule consisting of a route plan and a set of missions to accomplish for each ship on each day in the scenario.

NMP maximizes the total value of missions covered in the scenario by utilizing each ship to the best of its capabilities, while balancing the geographic distribution of missions, the limited capability of the ships, and the limited time horizon. This research explores the use of a heuristic for route generation within NMP to create alternative solutions in which the memory limited enumeration process cannot create. By exploring different methods of generating routes, a solution closer to the optimal solution can be found and explored.

Prior versions used a limited enumeration routine to generate a manageable number of routes for each ship. These prior models utilized optimization mathematical software to calculate the best solution out of the enumerated paths. Constrained by time and computational power, the enumeration method will stop before an exhaustive generation of all possible schedules and routes. Exploring other methods of route generation could produce routes not yet reached by enumeration. This research retains NMPs' use of Microsoft Excel, utilizing Visual Basic for Applications (VBA), a program more easily accessible on Department of Defense computer systems as compared to

licensed mathematical software. This allows the program to be computed at shore and afloat organizations without the need for outside resources.

We develop a heuristic route generator that reduces the runtime and provides better starting routes, improving the overall quality of solutions obtained by Navy Mission Planner. This model uses sixteen geographical areas, planned across a 15-day theater operation. This research produces a working model that provides a more effective solution than the doctrinal method of pen and paper. This method is not yet the optimal solution; however it is closer to the optimal solution than previous attempts.

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I would like to start by thanking my advisors Dr. Carlyle and CAPT (ret) Jeff Kline. Their support has really helped me attack this problem and ensure that I was finding those elements that I was missing throughout the entire process. I would also like to thank my academic associate, advisors, and chairs of the Undersea Warfare Department. Dr. Kapolka, RADM (ret) Ellis, RADM (Williams), and CDR Dumas, your support was extremely helpful and appreciated throughout my time at NPS. I will also mention the colleagues and friends I made who work out of office GL-270. Sometimes that laughter helped me relax enough to re-focus and continue this project. I value the friendships that have developed through this time. Next, I must show my appreciation to CAPT Alan "Dex" Poindexter, the former Dean of Students. Without his guidance, I surely would have gone down the wrong path in my studies and would never had made it this far. His recent passing is a terrible loss to the Navy and the NPS community. I would not be where I am today without him.

Finally, I must thank my wife. It has been a rough time over the past few years, with the tragedies we have shared, and the pressures we have gone through. You are a rock for me and I appreciate you continual re-focus on this project, even after I left the NPS campus. My gratitude is eternal. Thank you, and I love you very much.

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I. INTRODUCTION

A. PURPOSE AND OVERVIEW

The art of military planning is constantly improving, with an expanding set of tools developed to aid the military commander. As defined in Navy Warfare Publication (NWP) 5–01 (2007),

> Military planning is a comprehensive process that enables commanders and staffs at all levels and in all services to make informed decisions, solve complex problems, and ultimately accomplish assigned missions. Military planning is critical at every level of warfare—strategic, operational, and tactical—and in any situation regardless whether the threat is posed by a conventional military, an asymmetric unconventional adversary, or a combination of both. Furthermore, military planning can be applied whether conditions permit a lengthy, deliberate process or if the situation forces a compressed timeline. (NWP 5-01 2007, 1-1)

In an increasingly complex environment with enormous amounts of information available, planners need decision aids that represent military planning scenarios at reasonable levels of detail, are straightforward to use, and give solutions to these highly complex decision problems. These decision aids need to be able to process all of the complex information quickly and provide simplified output to decision makers. The most important service a decision aid provides is to take a difficult decision problem with complex data and provide insight to the decision maker about the choices to be made and what those choices mean.

The Navy Mission Planner (NMP) is an operational decision aid used to simultaneously optimize the employment of multiple naval combatant ships, each of which can be tasked with multiple, concurrent missions, in a campaign-level plan. Given a *planning horizon* represented as a fixed range of contiguous dates, a list of available naval *assets* and the dates on which they are available, a list of mission types that can be performed by naval assets, a list of geographic *regions* in which *missions* need to be assigned to ships, and a list of mission *values*, one for each mission type, in each region, on each day of the planning horizon, NMP will provide as output an *employment schedule* for each ship consisting of a sequence of geographical regions to visit, by day,

and a corresponding list of mission assignments for each of those regions, for each day. These employment schedules can then be used as a starting point by decision makers for further modification.

Dugan (2007) and Silva (2009) provide the basis for the Navy Mission Planner. This research is a continuation of their work and provides higher quality solutions with a heuristic algorithm. It simplifies the output given to the decision maker to make it more readily interpretable and, possibly, modifiable.

B. BACKGROUND

The United States Department of Defense uses doctrinal steps to plan all operations as it engages throughout the world. Joint Publication 5–0 lays out the planning process in detail for all members of the Department of Defense to follow. The United States Navy refines the planning process for its forces in Navy Warfare Publication 5–0: Navy Planning.

1. Navy Planning Process

The Navy Planning Process is broken up into six steps: Mission Analysis, Course of Action (COA) Development, COA Analysis (Wargaming), COA Comparison and Decision, Plans and Orders Development, and Transition. This progression creates a cycle, as shown in Figure 1. This continuous cycle starts at the highest echelons of the Navy's command structure and finishes at the person completing the tasking.

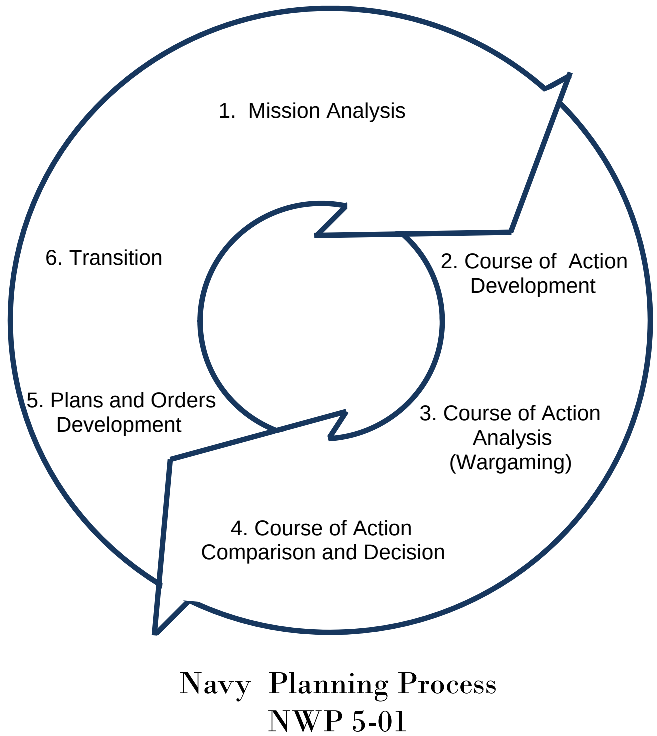

Figure 1. Navy Planning Process Cycle (From NWP 5–01 2007)

a. Mission Analysis

This step consist of examining all orders, and missions assigned from Higher Headquarters (HHQ)

b. Course of Action Development

The second step entails creating specific plans based off of the guidance from HHQ. This thesis focuses on this step in the Navy planning process. The output from the Navy Mission Planner is considered a plan to present for a COA.

c. Wargaming

COA analysis or wargaming requires a portion of the planning team to anticipate what the enemy's actions would be in the current situation. In this analysis, any strength or weakness in the COAs would be discussed. These discussions will determine the viability of any plan given to the Commander.

d. Comparison and Decision

The finalized COAs are presented to the Commander with the associated analysis of the plans and the overall situation. The commander makes the decision on which plan will be executed.

e. Orders Development

The Commanders staff then turns the decision into executable orders for all subordinates to carry out.

f. Transition

Finally, the orders are released and the next layer of units receives the orders. This move to the next lower echelon of commands then triggers the repeat of the planning process cycle and this new command starts back at step one.

2. Navy Mission Planner and Navy Planning

The Navy Mission Planner (NMP) was initially developed and formulated as a mathematical programming problem in Dugan (2007). It was further developed and described as a Joint Force Maritime Component Commander operational Planning Tool, in Silva (2009). The Navy Mission Planner is a decision aid designed to assist in the COA development and Wargaming stages of the Navy Planning Process.

C. SCOPE AND OBJECTIVES

This research's goal is to further expand the abilities of the Navy Mission Planner by exploring heuristic algorithms for generating higher-quality solutions than those provided by the current enumeration-based approach. Our new algorithm is designed to more completely explore the network, providing fewer, but higher quality ship employment schedules for use in the task assignment optimization model, thereby providing higher quality solutions to the overall mission planning problem. A secondary goal of this research is to create a competitive heuristic algorithm that can be run without requiring any commercial solvers. The algorithms we report in thesis can be run in

Microsoft Excel with Visual Basic for Applications (VBA), which is available on almost all standard U.S. Navy computers.

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II. NAVY MISSION PLANNER

A. NAVY MISSION PLANNER CONCEPT

In the maritime environment prior and during a major military operation, there are usually more missions that need to be accomplished than there are naval assets available. Some of these missions are multidimensional, in that they require more than one asset or resource, and some have limited time windows for assets to accomplish them. An advantage of a Navy ship is that it can complete several missions simultaneously in a short period of time. However, planning these maritime missions, by deciding to which ships they should be assigned, and when they should be accomplished, is not a simple task.

NWP 5–01 states that Navy Planning is currently done on paper, where a given list of missions is assigned to a component of the forces from the Operational Commander. It is then left up to the discretion of the component commander to assign units, (again, via paper), for tasking. This method is shown in Figures 2 and 3 using examples for Navy Planning from NWP 5–01. The inputs for these sheets are the missions to be completed, assigned assets available, and the general areas to perform the missions. While this is a process that has worked and has been developed into the planning cycle, it is time consuming and generally leaves various component commanders without the full picture of what is going on in the larger fleet while this planning cycle is occurring. This creates an issue when component commanders are trying to utilize assets for secondary missions, or are reliant on the full current tactical picture in order to start their planning cycle.

The data required to perform Navy Planning is a list of missions, a notion of priority for each mission (preferably expressed through a numerical value), the geographic area for each mission, and a list of available assets along with their capabilities and locations. Dividing missions among component commanders is a way of dealing with the large number of possible combinations of ships and missions by simplifying the problem: shorter lists of missions and assets can be matched up relatively

quickly, but this initial partition can miss some synergies between mission types and ship capabilities. A planning process that maintains visibility of all assets and missions, and makes mission assignments with the broader view in mind, is bound to provide more effective employment of all available Navy assets. If this planning process was also automated, it would allow for quick repetition of the process, the ability to quickly compute alternative plans, an exact reciprocation of the plan to all units, and the full plan for multiple days to be calculated in minutes and seconds rather than hours or days.

The Navy Mission Planner (NMP) is a decision support tool developed specifically for multi-ship, multi-mission planning, and uses brute-force enumeration combined with a large-scale optimization model to formulate and solve the multi-ship, multi-mission planning problem. NMP was first developed by Dugan (2007), and extended by Silva (2009).

Sketch:

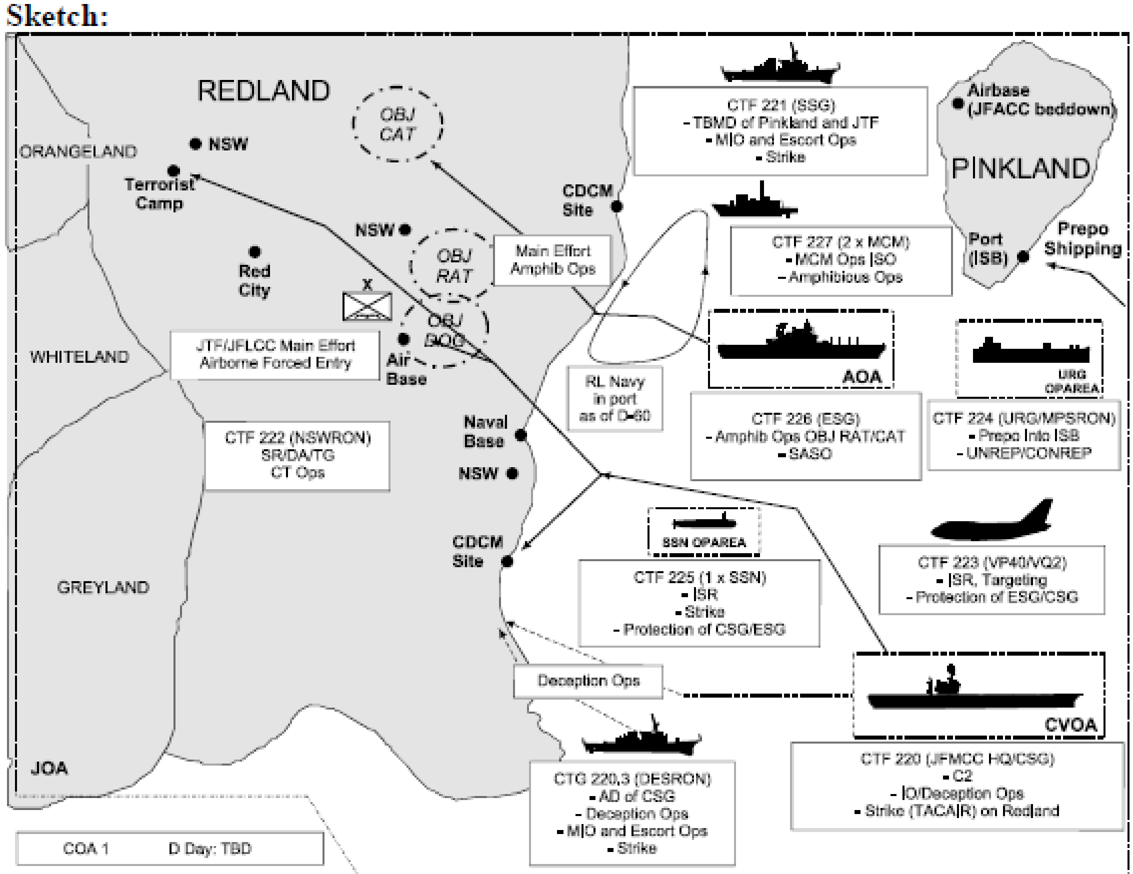

Figure 2. Sketch of a filled in example of a Navy Planning Worksheet from NWP 5–01 (2007) (Sheet 1 of 2)

COA #	Critical Event: Establish Maritime Superiority					
Sequence Number	**Friendly Action**	**Enemy Reaction**	**Friendly Counter Action**	**Time**	**Friendly Forces/ Assets**	**Remarks**
1	Conduct offensive SUW, USW and strike warfare (STW) to achieve maritime superiority	Conduct coordinated attacks using CDCM, hit-and-run tactics by surface ships, maritime strike aircraft, and diesel subs. Conduct covert mining.	Maintain layered defenses; increase offensive ops as necessary. Conduct MCM in impacted area.	2–5 days	CSG (CVW & CGs, and DESRON) SUBRON (SSNs) SSG (CG, DDGs) PATRON (VP/AIP)	Shortfall in MCM assets. Supplement to ROE needed for preemptive strikes on Redland mine storage facilities. Adjust PIR to look for indications of mining.
2	Additional rows if needed to continue action/reaction for this critical event.				Identify any items of concern that become apparent during the war game: force shortfalls, ROE needs, coordination issues, impact upon commander's governing factors, etc.	
3						

Figure 3. Sketch of a filled in example of a Navy Planning Worksheet from NWP 5–01 (2007) (Sheet 2 of 2)

B. LATEST FORMULATION OF NMP

In its most recent incarnation (Silva 2009), NMP generates hundreds of thousands of potential employment schedules for a given fleet of ships, (tens of thousands of schedules for each ship), and then, from that list, it optimally selects one schedule per ship and assigns a set of tasks to each ship. It is not able to generate all possible schedules, however, as the number of such schedules is prohibitively large; the number of schedules grows exponentially in the number of days in the planning horizon and in the number of distinct regions in which the ships can operate. The (relatively) few schedules that are generated are therefore a very small sample of the whole set of potential schedules. Because the enumeration in Dugan (2007) and Silva (2009) were simply truncated after a certain number of schedules were generated, the set of schedules is not as diverse as we would like. This leads to suboptimal solutions for which there are obvious improvements in individual ship schedules, and our observation of this fact led us to pursue a heuristic algorithm for route generation that would not suffer from the same limitations as truncated enumeration.

C. NMP GREEDY HEURISTIC FORMULATION

This formulation of NMP is based on Dugan (2007) and Silva (2009), where many of the index sets and required inputs are unchanged. However, in order to facilitate the development and implementation of a greedy heuristic we have made a few changes to the NMP formulation, and we present the complete, modified model below.

1. Sets and Indices [cardinality]

$s \in S$	Ship (hull number and name, alias *s'*) [~200]
$m \in M$	Mission type (alias *m'*) [~11] (e.g., AD, MIO, Intel TBMD)
$c \in C_s$	Concurrent binary mission capability set for ship *s* [~100]
$scl_s \in SCL$	Ship class. Each class of ship has general characteristics, and each ship belongs to a ship class [~9]
$m \in M_c$	Mission types in concurrent (simultaneous) mission set *c* (e.g., ship *s* can simultaneously perform mission type *m* in concurrent mission capability set *c*.)
$r \in R$	Regions in AOR [~30]
$d \in D$	Days in planning horizon (alias *d'*, *d"*) [~14]
$r(p,d)$	Region employment schedule *p* visits on day *d*
$n \in N$	Ordinal for multiple missions of the same mission type [~5] (e.g., several ships may conduct ASW at the same time within the same region, but with different effectiveness.)

2. Data [units]

$value_{m,n,r,d}$ Priority of n-th mission of type *m*, in region *r* on day *d* [1–20] [value] $\{m,n,r,d\} \in MNRD$ tuples exist only for non-zero values)

$accomplish_{s,scl_s,c,m}$ Level of accomplishment of concurrent mission set $c \in C_s$, mission $m \in M_c$ [0.0 - 1.0].

Each ship can only accomplish the mission if the ship is capable and the ship class is capable of the mission. (Note that each ship may have its own set of concurrent mission capability sets, and that some of these sets may contain the same missions, but with different accomplish rates to represent the ship choosing to change emphasis between missions.)

3. Induced Index Sets

$\{m,n,r,d\} \in MNRD$ 4-tuple exists only if value *m, n, r, d* > 0 or $accomplish_{s,scl_s,m} > 0$ for some ship that can employ a concurrent mission capability set that includes mission *m* in region *r* on day *d.* A concurrent mission set can be employed by a ship if the ship can accomplish it and the ship class can accomplish it.

$\{m,r,d\} \in MRD$ 3-tuple exists only if $\{m,n,r,d\} \in MNRD$ does for some *n*

$\{m,r,d,m'\} \in MRDM$ 4-tuple exists if, in region *r* on day *d*, mission *m* can be undertaken only if mission *m'* is fully accomplished

4. Variables [units]

$U_{m,n,r,d}$ Level of accomplishment of the *n*-th mission type *m* assignment

in region r on day d [0.0–1.0]

$V_{m,r,d}$	=1 if mission m is fully accomplished in region r on day d [binary]
$W_{s,c,d,r}$	=1 if ship s employs concurrent mission capability c on day d in region r [binary]
$X_{s,s',r,d}$	=1 only if ships s and s'' are both in region r on day d [binary]
Y_p	=1 if schedule p is selected [binary]

5. Formulation

$$\max \sum_{\{m,n,r,d\}\in MNRD} value_{m,n,r,d} U_{m,n,r,d} \qquad \text{(T0)}$$

$$\text{s.t.} \quad \sum_{p\in P_s} Y_p = 1 \qquad \forall s \in S \qquad \text{(T1)}$$

$$\sum_{c\in C_s} W_{s,c,d,r} \le \sum_{\substack{p\in P_s \\ \wedge \exists r(p,d)}} Y_p \qquad \forall s \in C_s, d \in D, r \in R \quad \text{(T2)}$$

$$\sum_{n|\{m,n,r,d\}\in MNRD} U_{m,n,r,d} \le \sum_{s\in S, c\in C_s} accomplish_{s,scl_s,c,m} W_{s,c,d,r}$$

$$\forall \{m,r,d\} \in MRD \qquad \text{(T3)}$$

$$V_{m,r,d} \le \sum_{\substack{p\in P \| r=r(p,d) \\ \wedge c\in C_{s(p)} \wedge m\in M_c}} accomplish_{s,scl_s,c,m} Y_p \qquad \forall \{m,r,d\} \in MRD \qquad \text{(T4)}$$

$$V_{m,r,d} \le \sum_{n|\{m,n,r,d\}\in MNRD} U_{m,n,r,d} \qquad \forall \{m,r,d\} \in MRD \qquad \text{(T4a)}$$

$$U_{m,n,r,d} \le V_{m',r,d} \qquad \forall m,n,r,d \,\big|\, \{m,n,r,d\} \in MNRD$$

$$\wedge \{m,r,d,m'\} \in MRDM \qquad \text{(T5)}$$

$$U_{m,n,r,d} \in [0,1] \qquad \forall \{m,n,r,d\} \in MNRD$$

$$V_{m,r,d} \in \{0,1\} \qquad \forall \{m,r,d) \in MRD$$

$$W_{s,c,d,r} \in \{0,1\} \qquad \forall s \in S, c \in C_s, d \in D, r \in R$$

$$Y_p \in \{0,1\} \qquad \forall p \in P$$

6. Discussion

The objective (T0) sums the total value of completed and partially completed missions. Each packing constraint (T1) allows exactly one employment schedule per ship. Each constraint (T2) permits a combatant to employ a concurrent mission capability on a given day only if an employment schedule exists for that ship. Each constraint (T3) limits the sum of the partial completion values of all missions by the total mission accomplishment for every tuple of mission, region, and day. Each constraint (T4) assigns full accomplishment to a mission in a particular region on a particular day only if there is at least one total unit of accomplishment for that same combination of mission, region, and day. Similarly, each constraint (T4a) assigns full accomplishment to a mission in a particular region on a particular day only if each mission copy combines in that region on that day to produce at least one total unit of accomplishment. Constraints T4 and T4a are equivalent for determining optimal employment schedules, *Y*, but T4a enforces additional structure on the individual mission accomplishment variables, *U*, for prerequisite missions that have no prescribed value. Each constraint (T5) ensures that no mission accrues accomplishment in a given region on a given day unless each of its prerequisite missions (if any) in that region on that day has full accomplishment. (T6) defines the variable domains.

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III. HEURISTIC SOLUTION GENERATION FOR NAVY MISSION PLANNER

A. EMPLOYMENT SCHEDULE GENERATION

The prior version of the Navy Mission Planner (Silva 2009) uses brute-force enumeration of employment schedules until reaching an upper limit on the number of schedules generated. It then chooses the most valuable assignment of employment schedules to ships from that given set of schedules. Generating the employment schedules with that kind of heuristic will not exploit the entire graph. For any reasonable maximum number of schedules, the depth-first enumeration will not create a diverse set of schedules for any single platform. In fact, most schedules will be identical for the first several days of the planning horizon, and there is no tendency in the depth-first search to choose sequences of regions that allow a platform to be assigned to high-value missions. A different approach is needed to explore the graph in a more diverse way and increase the likelihood that high-quality schedules are generated.

1. Modifications to NMP Schedule Generation

The brute-force enumeration used by previous versions of NMP (as described in Silva 2009) is based on a truncated version of stack-based, depth-first exploration of the graph created to represent all of the geographic regions in a scenario and their relative positions to each other, using backtracking and a simple bookkeeping procedure to prevent repetition (W. M. Carlyle, personal communication on Heuristic Enumeration and Greedy Algorithms, May 10, 2011). For each ship, the algorithm takes its starting region and produces a sequence of regions, one region per day in the planning horizon, which represents a feasible movement plan for that ship. These sequences allow for the possibility that a ship might remain in the same region for several days in a row, or even return to a region it had previously left. This stack-based enumeration is straightforward on most graphs, and can be implemented to generate hundreds of thousands, or even millions, of these movement plans in a very short time. Unfortunately, the most direct implementations of these algorithms tend to enumerate a large number of very similar

paths. In the cases we studied, the first ten thousand paths for a given ship, over a 15-day horizon, stayed in the same three or four regions (out of 24) and showed infrequent movement between those regions. Diversity in the paths only happens after incredibly large numbers of fairly similar paths (billions or trillions, or even more for longer time horizons) have been considered.

The solutions produced by NMP suffer from this lack of diversity; it never enumerates enough movement plans to provide any variety, and the resulting employment schedules cannot cover the missions as completely as we would like. Visual inspection of the solutions reveals this lack of variety. There are several possibilities for modifying the enumeration algorithm to explore the graph (including the remote areas) more thoroughly in a smaller number of paths.

In addition to improving the enumeration, which simply provides these lists of movement plans as an input to the optimization model that then selects one plan per ship, we can also try to generate a *single*, complete employment schedule for each ship using a heuristic algorithm. This would generate the movement plan and the mission assignments simultaneously, and try to do so in a way that covers as many *currently uncovered* high-value missions as possible. The hope is that bypassing the enumeration and subsequent optimization allows the heuristic to generate reasonable solutions extremely quickly, and that this process can be repeated to create several alternative options for a commander to consider.

a. Modification of the Backtracking Algorithm

We create more diversity in the set of enumerated movement plans by backtracking more aggressively; when our depth-first algorithm backtracks and removes one node from the top of the current path stack, we remove more than one node. This means we skip many paths, but it also means that the initial sequences of nodes will change much more frequently and lead to a more diverse set of paths. Our testing of aggressive backtracking involves removing two nodes at a time. The benefit to implementing a more aggressive backtracking rule is that the current build of NMP can be modified with this rule and new results can be computed easily. The current build does

produce feasible results with this scheme, and solutions that are of higher quality than those reported in Silva (2009).

b. Greedy Heuristic with NMP

The current build of NMP focuses on developing the paths for the ships to travel, and then places a ship along the path to calculate the maximum value that ship can acquire. Alternatively, a greedy heuristic is used to associate as much value to ships immediately without having to enumerate all of the paths first. The program will generate only one path for each ship, maximizing the value gained with the given constraints. Without the enumeration, the computation speed is decreased, making a better decision aid for an operational level planner. This method cannot guarantee an optimal result, and should be evaluated against other methods whenever possible to determine whether it tends to produce acceptable solutions. We found that such a heuristic can provide significant improvements over the enumeration and optimization strategy in Silva (2009).

2. New Direction

This research focuses on the development and execution of a greedy heuristic for NMP. The purpose for conceiving a greedy algorithm for the Navy Mission Planner is tied into the specific goals of this research. These goals are to eliminate the need for use of the commercial software Generic Algebraic Modeling System (GAMS)[1] and diminish the gap between the model and inputs from the Navy. In order to accomplish these primary goals, this research strives to achieve a feasible solution from a greedy heuristic and provide a solution comparable to solutions already produced by the model that uses GAMS. By working towards being greedy across all days and regions, it is believed that the greedy heuristic solution provides a feasible solution that is equivalent to the solution computes by GAMS.

[1] GAMS Development Corporation (2009). General Algebraic Modeling System [computer software]. Washington, DC. Available from http://www.gams.com/.

3. Modifying the Navy Mission Planner

By using a greedy heuristic, NMP will be able to create a solution without having to enumerate many paths and then optimize the path chosen using commercial optimization software. Such commercial optimization packages are not currently incorporated into the computer systems used by the United States Navy. The heuristic algorithm we develop below has been implemented in Microsoft Excel, using Visual Basic for Applications (VBA)[2], and this tool is available Navy-wide.

B. IMPLEMENTING A GREEDY HEURISTIC

1. Definitions

The first element to define is the base elements in our model. These base elements were introduced in the NPS Formulation used in Chapter II. Those elements include the set of each ship s is part of the larger set S, written as $s \in S$. Other base sets are the mission set M, $m \in M$, the regions in the operational area, $r \in R$, and days of the planning window, $d \in D$. A new element integrated in this research was a second definition for ships. While each ship belongs to the list of ships, each ship also belongs to a class of ship. For example, the USS JOHN PAUL JONES (DDG 53) is a member of the list of all the ships in the Navy, it is also a member of the class of ships DDG. This is important to note that members of the same ship class have similar capabilities.

Next, we define elements that are unique to the pseudocode. There are some elements that are used in the NPS Formulation that were also used in the pseudocode. There are also other elements that are covered by the NPS Format, but to cover in pseudocode are recreated and defined in the method to be used in coding.

a. Pairwise Binary Capability Matrix

The pairwise binary capability matrix for each ship class is defined by a 13-tuple with the first element being the ship class (1–9, each number relating to a ship

[2] Microsoft Corporation (2013). Visual Basic for Applications [computer software]. Redmond, WA. Available from http://www.microsoft.com

class [DDG, CG, FFG, etc.]), the second is one the eleven mission types (AD, SUW, ASW, etc.) and then elements three through thirteen are the pairwise binary capability of that ship to perform one of the eleven mission types if it is already engaged in the mission type in element two. Being a binary pairwise preclusion constraint enforces the limitations of a class of ships, stating whether it is systematically possible for a ship of that class to execute a mission filling position three through thirteen based off of that class of ship already executing the mission in position two. That produces eleven 13-tuples for each class of ship. These tuples are grouped into a term labeled $bincaptuple_{c_s,m,m'}$. It is important to note that the diagonals of this matrix will show all the missions that this class of ship can accomplish as individual mission.

b. Ship Capability Matrix

Each ship may have limitations in completing particular missions due to system casualties, lack of personnel, or low weapon inventories. This design is in addition to the pairwise preclusion constraint. By removing impossible missions for the class of ship, the individuality of a ship can be utilized to uniquely figure out missions, or more importantly the percent accomplishment of missions to be done by an individual ship. This matrix, labeled $shipcaptuple_{s,m}, \forall s \in S$, is a 12-tuple with the first element being a value tied to a specific ship and elements two through twelve being a degradation of one of the mission types [0.0–1.0]. These degradations are ship specific for a mission type.

The ship capability matrix is specifically identified for an individual ship. It does incorporate some of the limitations introduced by the binary pairwise capability matrix. For example the ship the USS VELLA GULF (CG 72) has a value of zero for the mission MCM. The binary pairwise matrix for CG also has a zero for MCM (Table 1). The purpose behind having both is that the pairwise matrix expands the capabilities of the ship specific matrix to show the compatibility between missions. In the sample table below for the USS VELLA GULF (Table 2), the ship is fully capable to accomplish the AD and TBMD missions; however, if you look at the CG capability matrix it shows that those two missions are incompatible (Table 3). Many ships in the Navy were designed to

be multi-mission platforms, and excel at accomplishing more than one mission at a time. However, some systems have limitations that exclude them from being executed at the same time as other missions.

Ship	Name	Avail	Class	Type	Start Day	Start Region	NSFS	MIO	MCM	Mine	Intel
CG 72	VELLA GULF	x	CG	COMBAT	4	r7	0.5	1	0	0	1

Table 1. Sample of USS VELLA GULF Ship compatibility Matrix (Part 1 of 2)

Ship	Name	Avail	Class	Type	Start Day	Start Region	AD	TBMD	ASW	SUW
CG 72	VELLA GULF	x	CG	COMBAT	4	r7	1	1	1	0.5

Table 2. Sample of USS VELLA GULF Ship compatibility Matrix (Part 2 of 2)

CG	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
AD	1	0	1	1	0	0	1	0	0	1	0
TBMD	0	1	1	1	0	0	0	0	0	1	0
ASW	1	0	1	1	1	0	1	0	0	1	0
SUW	1	0	1	1	1	1	1	0	0	1	0
Strike	1	0	0	1	1	0	1	0	0	1	0
NSFS	1	1	0	1	0	1	0	0	0	1	0
MIO	1	1	1	1	1	0	1	0	0	1	0
MCM	0	0	0	0	0	0	0	0	0	0	0
Mine	0	0	0	0	0	0	0	0	0	0	0
Intel	1	1	1	1	1	1	1	0	0	1	0
SubIntel	0	0	0	0	0	0	0	0	0	0	0

Table 3. CG Binary Pairwise Preclusion Constraint

c. *The Stack Array*

This pseudocode is written so that each ship in the set *S* is a stack in memory. The height of the stack is the length of the planning window for the scenario, in this case 15 days. The input of the stack is the region to which it travels, labeled *regionstack()*. The stack array takes the day as input and the region is stored as output. Each ship has its own stack. On the start day the input into the stack is the start region (label *startregion*). It is zero for all days before the start day. The term *top* refers to the top position in the stack and is set to the current region. For the beginning of the

heuristic, the top is the start region. Top is referenced by the day, with the first day being *startday*. When looking at specific regions and days, they may be referred to as *currregion* and *currday*. The stack, however, has a defined limit. For this specific scenario it is contained at 15 days. This definition is known as the *lastplanday* and can be modified to extend or shorten the planning window.

d. Other Required Definitions

In order to temporarily store information a number of temporary arrays and variables are created. These are all laid out as *tempday* and *tempregion*. The strong suit of this heuristic is that it will move the unit if it determines that more value can be obtained from other regions. This requires travel of the vessels, so distances from regions had to be calculated. The distance is labeled d_{ij}. Another facet of this heuristic is that the ships can be made to travel to regions not touching an adjacent region. In order to determine which regions are not adjacent, a range of travel in one day period had to be calculated, and is labeled *DayRange*. An adjacent region is any node that can be reached during a night transit, defined as travel speed over an 8-hour period. Any region outside of that range will take at least one day of transit to reach, during which the ship will not be able to accomplish missions.

e. Subroutines

The final aspect of the psuedocode is the subroutines that it runs. There are five subroutines. The first two, *primarymission* and *primarystoremission*, calculate and store the main mission for a region. It is the highest value mission in that region on that day that the specific ship can accomplish. Once the mission is found, the mission, location, and day is stored for recall later. The next pair of subroutines is for the secondary missions, labeled *secondarymissions* and *secondarystoremissions.* The units involved are capable of completing multiple missions at the same time, depending on ship class and specific ship limitations. Any mission that is available for a ship to pick up while accomplishing the primary mission is found and stored for later recall. The final subroutine is called *findnextregionandday*. This subroutine is a do-loop that will loop through each future day without going outside the planning window. It calculates the

most attractive region for the ship to head to next, regardless of distance or days. These definitions provide a guide through the pseudocode.

2. Greedy Heuristic Pseudocode

Main Routine

Inputs: $value_{m,r,d,m}$ $bincaptuple_{scl_s,m}$ $shipcaptuple_s$

Outputs: *regionstack(), s*

For each ship *s* in rShips
    Clear *regionstack()*
    top := startday, regionstack(top) := startregion (P1)

    For each *day* from 0 to *startday* - 1
        Push a zero (i.e., no region) onto the stack
    Next *day* (P2)
    Set *d = startday* and *r= startregion*
    If there is a mission *m* in this region with a non-zero value, that
        ship s can accomplish, on this day, then
        Set incumbent to be the first mission with nonzero value in region *r*
        on day *d*.
    Else
        Set incumbent to *startregion* and the $value_{m,r,d,m}$ to zero.
    End If

    If $value_{m,regionstack(top),top,m}$ exist then run *primarymission* subroutine
        Run *primarystoremission* subroutine
        Run *secondarymissions* subroutine
        Run *secondarystoremissions* subroutine
    Else
        Temporarily store the start region and start day and a value of 0
    End if

    Run *findnextregionandday* subroutine

    top := top + travel days to highest value region, regionstack(top):=
        highest value region (P3)
Write *s, regionstack()* into an output file (P4)

***Primarymission* subroutine**

Inputs: *m*, $value_{m,r,d,m}$, *r*

Outputs: *r, m, d*

For each $m \in M$, $value_{m,n,r,d} = value_{m,n,r,d} bincaptuple_{SCL,m}$

determine the largest $value_{m,r,d,m}$, where r:= tempregion and d:= tempday and $accomplish_{s,scl_s,m} < 1$

next *m*

Store the region, day, and mission into a temporary stack

***Secondarymission* subroutine**

Inputs: m’, r, d

Outputs: m, r, d

For each $m \in M$, $m' :=$ mission from primarymission, and $m \neq m'$

$value_{m,n,r,d} = value_{m,n,r,d} bincaptuple_{SCL,m'}$

If $value_{m,n,r,d} > 0$ and r:= currregion and d:= currday and

$accomplish_{s,scl_s,m} < 1$

Store the region, day, and mission into a temporary stack

End If

next m

***Primarystoremission* subroutine**

Inputs: *m, r, d*

Outputs: *s, m, r, d*

$accomplish_{s,scl_s,m} = value_{m,r,d,m} shipcaptuple_s$

Store the ship, region, day, and mission into a temporary stack

If $accomplish_{s,scl_s,m} \geq 1$ then mark the region,day,mission as complete

***Secondarystoremission* subroutine**

Inputs: *m', r, d*

Outputs: *s, m, r, d*

For $m' :=$ mission from primarystoremission

For each $m \in M$

$accomplish_{m,r,d} = value_{m,r,d,m}(bincaptuple_{scl,m}, shipcaptuple_s)$

Store the ship, region, day, and mission into a temporary stack

If $accomplish_{s,scl_s,m} \geq 1$ then mark the region,day,mission as complete

Next m

Findnextregionandday subroutine

Inputs: $dij(regionstack(top), r)$, DayRange, regionstack(top)

Outputs: $value_{m,r,d,m}$, r, d

For each day *d* from *startday+1 to lastplanday*

Tempday:=d'

For each d' from startday+1 to lastplanday

For each $r \in R$*, where*

$dij(regionstack(top), r) < d * DayRange$

Determine the highest value r within d'*DayRange by running primarymission subroutine and running secondarymissions subroutine, and comparing the values:

$$value_{m',n,r,d} = \frac{(\sum_{\forall m \in M} value_{m',n,r,d}, r := tempregion)}{tempday} \quad \text{(P5)}$$

Next r

Store the region, day, and calculated value of the highest value into a temporary stack

Next d' (P6)

Store the region, day, and calculated value into a temporary stack

Next d

3. Pseudocode Discussion

The top of the stack is set to the specific ship's start day and the ship's start region (P1). All other locations on the stack are 0. The ship will start in its designated start location. If there is no value in that location, then it is a "wasted" day (P2). The value in the position of *top* at the end of a run of the heuristic places the highest value region on the stack in the position of the top of the stack plus the travel day(s) (P3). Once the program has looped through each day of the planning window, the stack is printed to an output file. The file will record the Ship, regions visited on which days, missions accomplished, and the value of those missions. Those accomplished missions and values are subtracted from the overall matrix of possible values, the ship, and missions are marked complete, and the stack is reset. The program moves onto the next Ship in the available ship list or next S (P4). In calculating the most desirable region, the incompatible regions are filtered out, and the ship is guaranteed those gain this value. The value equation (P5) calculates the highest value in a region and then divides it by the day range. It will predict out to the end of the planning window to ensure that the value the ship is traveling for is greater than a value that is closer. The loop over each day (P6) will compare the highest value of each subsequent day compared to the highest value saved. This method will use an expanding day range of travel to get the best value. If the program finds a value of 3 in a region that is one day away, but finds 24 points 7 days away, it will travel the 7 days (24/7 = 3.4285) and forgo the 3 points and points in the regions between the 3 points and the 24 points. However, if it were only 20 points 7 days away, it would not travel for those points (20/7 = 2.857). Once the planning window from day 1 to the last planning day is complete, it will move on to the next ship. The program completes once it has a schedule for each ship.

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IV. SCENARIO, ANALYSIS, AND CONCLUSION

A. ORIGINAL NAVY MISSION PLANNER MODEL

The initial design of NMP tested a scenario of 40 ships, operating in 24 different regions over a time period of 15 days, with 65 separate missions identified. It utilized an enumeration algorithm in order to create an employment schedule for a ship. This enumeration would generate all the paths a ship could take and then take the best of all of them. Dugan provided a proof of concept for NMP and showed the benefits of an automated algorithm in order to assist and speed up the process for Maritime planning.

The other element in the model to emulate reality is concurrent mission capability sets (CMCs). Naval vessels have been designed with the ability to accomplish multiple missions at once, but not every ship can do all of the missions stated above. CMCs show that while a ship is working on some mission types, other mission types might be degraded. Other missions may completely exclude the ability to accomplish another mission. The CMCs express the real constraints inherent in our shipboard systems (Table 4).

		Mission										
Ship Class	**CMC**	**AD**	**TBMD**	**ASW**	**SUW**	**Strike**	**NSFS**	**MIO**	**MCM**	**Mine**	**Intel**	**SubIntel**
CG	C1	1	0	1	1	1	1	0	0	0	1	0
	C2	1	0	0.5	1	1	0.75	0	0	0	1	0
	C3	1	0	1	0.5	1	0.5	0	0	0	1	0
	C4	1	0	0	1	1	1	0	0	0	1	0
	C5	1	0	0	1	1	0	1	0	0	1	0
	C6	1	0	0	0.5	1	0	1	0	0	1	0
	C7	0	1	1	1	1	1	0	0	0	1	0
	C8	0	1	0.5	1	1	0.75	0	0	0	1	0
	C9	0	1	1	0.5	1	0.5	0	0	0	1	0
	C10	0	1	0	1	1	1	0	0	0	1	0
DDG	C11	1	0	1	1	1	1	0	0	0	1	0
	C12	1	0	0.5	1	1	0.75	0	0	0	1	0
	C13	1	0	1	0.5	1	0.5	0	0	0	1	0
	C14	1	0	0	1	1	1	0	0	0	1	0
	C15	1	0	0	1	1	0	1	0	0	1	0
	C16	1	0	0	0.5	1	0	1	0	0	1	0
	C17	0	1	1	1	1	1	0	0	0	1	0
	C18	0	1	0.5	1	1	0.75	0	0	0	1	0
	C19	0	1	1	0.5	1	0.5	0	0	0	1	0
	C20	0	1	0	1	1	1	0	0	0	1	0
FFG	C21	0	0	1	1	0	0	0	0	0	0	0
	C22	0	0	0.5	1	0	0	0	0	0	0	0
	C23	0	0	1	0.5	0	0	0	0	0	0	0
	C24	0	0	0.67	0.67	0	0	0	0	0	0	0
	C25	0	0	0	1	0	0	1	0	0	0	0
	C26	0	0	0	0.5	0	0	1	0	0	0	0
LCS	C27	0	0	1	0	0	0	0	0	0	0	0
	C28	0	0	0	1	0	0	1	0	0	0	0
	C29	0	0	0	0.5	0	0	1	0	0	0	0
	C30	0	0	0	0	0	0	0	1	0	0	0
SSN	C31	0	0	1	1	0	0	0	0	0	0	0
	C32	0	0	1	0.5	0	0	0	0	0	0	0
	C33	0	0	0.5	1	0	0	0	0	0	0	0
	C34	0	0	1	0	0	0	0	0	0	0	0
	C35	0	0	0	0	1	0	0	0	0	0	0
	C36	0	0	0	0	0	0	0	0	1	0	0.5
	C37	0	0	0	0	0	0	0	0	1	0	1
SSGN	C38	0	0	0	0	1	0	0	0	0	0	0
	C39	0	0	0	0	0	0	0	0	1	0	0.5
	C40	0	0	0	0	0	0	0	0	0.5	0	1
MCM	C41	0	0	0	0	0	0	0	1	0	0	0

Table 4. List of Concurrent Mission Capability Sets (CMCs) used in NMP

B. CONCURRENT MISSION CAPABLE SETS MODIFICATIONS

The other goal of this research is closing the gap of the model and reality. Dugan (2007) introduced the idea of Concurrent Mission Capable sets (CMCs). They exclude and include various missions based off of settings that would affect a ship class. While the focus is on the ship, it is not a generic set that applies to all members of that class of ship. Therefore, when a new element is required, due to a ship change or a ship class change, a new CMC must be created, inputted and then applied to all members it affects, and the model re-run. To a user, this matter is not trivial. Implemented incorrectly it could render the calculations computed by GAMS and Excel invalid. The Navy builds its assets as classes, which have the same abilities overall, but will have minor modifications from ship to ship. CMCs do not currently have the capacity to reflect the individuality of a ship and focus on the class as a whole. This research replaces the CMCs with two sets of tuples. The first set is based on classes of ships and does not get modified. The second set is ship specific and allows for modification to reflect the most current information available.

1. Ship Class Binary Preclusion Constraint

The first set of tuples is a more robust and generic set created for each class of ship. A ship class is defined by the traits that ships hold common to each other and is designated by the military. All Guided Missile Destroyers (DDGs) have similar capabilities but would have different capabilities than Fast-Attack Submarines (SSNs). In order to add additional aspects of realism, ship class binary preclusion constraints were created. These binary pairwise preclusion constraints evaluates each mission type and provides a binary value for the ability of a ship class to conduct any other mission while it is engaged in a primary mission. Tables 5–12 are the pairwise comparisons of platform specific limitations common for all ships belonging to a ship class. This data was derived from the CMCs developed for Silva (2009) and further refined during discussions with Jeffrey Kline, CAPT, USN (retired), an advisor on naval systems to the NMP project and also a contributor to Silva (2009) (J. E. Kline, personal communication on Ship Capability Limitations (February 11, 2011)

The tables are read in the following manner. First determine the ship class to reference the correct table. Then read down the left column until the primary mission of interest is found. Reading across the row from the primary mission is a binary interpretation of whether a mission is able to be accomplished during the same time the primary mission is being accomplished. This determination is based off of ship systems limitations and system exclusions. For example if a DDG was engaged in a primary mission of AD (first row entry on the left column), it could also conduct a mission of SUW (fifth column), but it could not complete TBMD (third column). These values do not require modification and remain stable because the abilities of the specific class do not change. This binary preclusion constraint is represented in the formula by a thirteen element tuple, where the first element represents the class of ship (for example DDG), the second element is the associated value for a mission type relating to the primary mission (AD is one, TBMD is two, etc.). Elements three through thirteen are the binary inputs as you go from left to right across the table. Therefore, a DDG class of ship with a primary mission of AD would have the elements three through thirteen read as follows; 1, 0, 1, 1, 0, 0, 1, 0, 0, 1, 0.

This method of labeling limitations is an improvement over the previous CMCs. It allows for one set of constraints to be generated for multiple ships of similar designs. As the number of ships in the Navy fluctuates, these parameters in the ship class constraint will not need to change. This also allows for an unlimited number of ships to be added or subtracted from the available unit list without having to modify or create a new CMC to satisfy the capabilities of that unit.

CG	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
AD	1	0	1	1	0	0	1	0	0	1	0
TBMD	0	1	1	1	0	0	0	0	0	1	0
ASW	1	0	1	1	1	0	1	0	0	1	0
SUW	1	0	1	1	1	1	1	0	0	1	0
Strike	1	0	0	1	1	0	1	0	0	1	0
NSFS	1	1	0	1	0	1	0	0	0	1	0
MIO	1	1	1	1	1	0	1	0	0	1	0
MCM	0	0	0	0	0	0	0	0	0	0	0
Mine	0	0	0	0	0	0	0	0	0	0	0
Intel	1	1	1	1	1	1	1	0	0	1	0
SubIntel	0	0	0	0	0	0	0	0	0	0	0

Table 5. Ship Class Preclusion Constraint Table for CG

CVN	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
AD	1	0	0	0	0	0	0	0	0	1	0
TBMD	0	0	0	0	0	0	0	0	0	0	0
ASW	0	0	0	0	0	0	0	0	0	0	0
SUW	0	0	0	0	0	0	0	0	0	0	0
Strike	0	0	0	0	1	0	0	0	0	1	0
NSFS	0	0	0	0	0	0	0	0	0	0	0
MIO	0	0	0	0	0	0	0	0	0	0	0
MCM	0	0	0	0	0	0	0	0	0	0	0
Mine	0	0	0	0	0	0	0	0	0	0	0
Intel	1	0	0	0	1	0	0	0	0	1	0
SubIntel	0	0	0	0	0	0	0	0	0	0	0

Table 6. Ship Class Preclusion Constraint Table for CVN

DDG	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
AD	1	0	1	1	0	0	1	0	0	1	0
TBMD	0	1	1	1	0	0	0	0	0	1	0
ASW	1	0	1	1	1	0	1	0	0	1	0
SUW	1	0	1	1	1	1	1	0	0	1	0
Strike	1	0	0	1	1	0	1	0	0	1	0
NSFS	1	1	0	1	0	1	0	0	0	1	0
MIO	1	1	1	1	1	0	1	0	0	1	0
MCM	0	0	0	0	0	0	0	0	0	0	0
Mine	0	0	0	0	0	0	0	0	0	0	0
Intel	1	1	1	1	1	1	1	0	0	1	0
SubIntel	0	0	0	0	0	0	0	0	0	0	0

Table 7. Ship Class Preclusion Constraint Table for DDG

FFG	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
AD	0	0	0	0	0	0	0	0	0	0	0
TBMD	0	0	0	0	0	0	0	0	0	0	0
ASW	0	0	1	1	0	0	0	0	0	1	0
SUW	0	0	1	1	0	0	1	0	0	1	0
Strike	0	0	0	0	0	0	0	0	0	0	0
NSFS	0	0	0	0	0	0	0	0	0	0	0
MIO	0	0	0	1	0	0	1	0	0	1	0
MCM	0	0	0	0	0	0	0	0	0	0	0
Mine	0	0	0	0	0	0	0	0	0	0	0
Intel	0	0	1	1	0	0	1	0	0	1	0
SubIntel	0	0	0	0	0	0	0	0	0	0	0

Table 8. Ship Class Preclusion Constraint Table for FFG

LCS	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
AD	0	0	0	0	0	0	0	0	0	0	0
TBMD	0	0	0	0	0	0	0	0	0	0	0
ASW	0	0	1	0	0	0	0	0	0	1	0
SUW	0	0	0	1	0	1	1	0	0	1	0
Strike	0	0	0	0	0	0	0	0	0	0	0
NSFS	0	0	0	1	0	1	0	0	0	1	0
MIO	0	0	0	1	0	0	1	0	0	1	0
MCM	0	0	0	0	0	0	0	1	0	1	0
Mine	0	0	0	0	0	0	0	0	0	0	0
Intel	0	0	1	1	0	1	1	1	0	1	0
SubIntel	0	0	0	0	0	0	0	0	0	0	0

Table 9. Ship Class Preclusion Constraint Table for LCS

MCM	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
AD	0	0	0	0	0	0	0	0	0	0	0
TBMD	0	0	0	0	0	0	0	0	0	0	0
ASW	0	0	0	0	0	0	0	0	0	0	0
SUW	0	0	0	0	0	0	0	0	0	0	0
Strike	0	0	0	0	0	0	0	0	0	0	0
NSFS	0	0	0	0	0	0	0	0	0	0	0
MIO	0	0	0	0	0	0	0	0	0	0	0
MCM	0	0	0	0	0	0	0	1	0	1	0
Mine	0	0	0	0	0	0	0	0	1	1	0
Intel	0	0	0	0	0	0	0	1	0	1	0
SubIntel	0	0	0	0	0	0	0	0	0	0	0

Table 10. Ship Class Preclusion Constraint Table for MCM

SSGN	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
AD	0	0	0	0	0	0	0	0	0	0	0
TBMD	0	0	0	0	0	0	0	0	0	0	0
ASW	0	0	1	1	0	0	0	0	1	0	1
SUW	0	0	1	1	1	0	0	0	1	0	1
Strike	0	0	0	1	1	0	0	0	1	0	1
NSFS	0	0	0	0	0	0	0	0	0	0	0
MIO	0	0	0	0	0	0	0	0	0	0	0
MCM	0	0	0	0	0	0	0	0	0	0	0
Mine	0	0	1	1	0	0	0	0	1	0	1
Intel	0	0	0	0	0	0	0	0	0	0	0
SubIntel	0	0	1	1	1	0	0	0	1	0	1

Table 11. Ship Class Preclusion Constraint Table for SSGN

SSN	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
AD	0	0	0	0	0	0	0	0	0	0	0
TBMD	0	0	0	0	0	0	0	0	0	0	0
ASW	0	0	1	1	0	0	0	0	0	0	1
SUW	0	0	1	1	0	0	0	0	1	0	1
Strike	0	0	0	0	1	0	0	0	0	0	1
NSFS	0	0	0	0	0	0	0	0	0	0	0
MIO	0	0	0	0	0	0	0	0	0	0	0
MCM	0	0	0	0	0	0	0	0	0	0	0
Mine	0	0	0	1	0	0	0	0	1	0	1
Intel	0	0	0	0	0	0	0	0	0	0	0
SubIntel	0	0	1	1	1	0	0	0	1	0	1

Table 12. Ship Class Preclusion Constraint Table for SSN

2. Ship Specific Limitation Set

In order to address reality and the individual differences among each ship, another table was created. This table encompasses all the ships in the United States (U.S.) Navy and is represented in the formula by a twelve element tuple. The first element is the associated number for the ship, and elements two through twelve are the ships individual capability to perform a mission. The binary preclusion constraint restricts a class of ships and their ability to perform missions based off of missions and system limitations. The ship specific preclusion constraints limit the accomplishment of the mission due to any effect on the mission, whether it is a personnel issue, or an equipment issue. Therefore, to be effective in accurately portraying accomplishment of the missions, they need to be used together. Tables 13 and 14 are presented as a portion of the ships in the United States Navy, but encompass the entire list of ships used in this research. The table describes the ship name, ship class, the start day, and start region for this research. For a complete list of all vessels used by the United States Navy, please consult the Naval Vessel Register (http://www.nvr.navy.mil/).

This table also shows the specific ship limitations as tested in this research. The specific ship limitations concept was created to pair with the Ship Class Preclusion Constraints. While the preclusion constraints relate to a ship class, these address limitations to a specific ship. The limitations as presented below are representative of matters relating to a specific ship. These issues could be personnel manning or ship specific system issues. The information used below was derived from CMCs as presented

in Silva (2009), and further refined during discussions (J. E. Kline, personal communication February 11, 2011). The data is developed specifically for this research.

The benefit to this method of limitations for ships versus the CMCs is in the ease of adaptation of individual ships and future integration into U.S. Navy command systems. Adding the specific limitations for individual ships allows for further refinement in mission capabilities. Without these, generic planning can happen. However, once a unit is decided upon, a more accurate reflection of that unit's capabilities can be utilized to create the best plan possible. Currently, there are methods for reporting personnel and systems statuses that are central to key missions for the U.S. Navy. This database of information, which provides a percentage capability for the mission types, could be connected into the ship specific preclusion constrains. While the processing time of the model is not increased it does provide a template for integration into U.S. Navy systems.

Ship	Name	Avail	Class	Type	Start Day	Start Region	AD	TBMD	ASW	SUW	Strike	NSFS
CG 58	PHILIPPINE SEA	x	CG	COMBAT	7	r10	1	1	1	1	1	1
CG 61	MONTEREY	x	CG	COMBAT	1	r2	1	1	1	1	1	1
CG 66	HUE CITY	x	CG	COMBAT	1	r13	1	1	0.5	1	1	0.75
CG 72	VELLA GULF	x	CG	COMBAT	4	r7	1	1	1	0.5	1	0.5
DDG 53	JOHN PAUL JONES	x	DDG	COMBAT	1	r1	1	1	1	1	1	1
DDG 62	FITZGERALD	x	DDG	COMBAT	1	r4	1	1	1	1	1	1
DDG 80	ROOSEVELT	x	DDG	COMBAT	4	r5	1	1	1	1	1	1
DDG 86	SHOUP	x	DDG	COMBAT	1	r9	1	1	0.5	1	1	0.75
DDG 90	CHAFEE	x	DDG	COMBAT	1	r7	1	1	0.5	1	1	0.75
DDG 97	HALSEY	x	DDG	COMBAT	7	r11	1	1	1	1	1	1
DDG 100	KIDD	x	DDG	COMBAT	4	r13	1	1	1	0.5	1	0
DDG 104	STERETT	x	DDG	COMBAT	4	r4	1	1	1	1	1	1
FFG 47	NICHOLAS	x	FFG	COMBAT	7	r8	0	0	0	0.5	0	0
FFG 48	VANDEGRIFT	x	FFG	COMBAT	4	r10	0	0	0	1	0	0
FFG 52	CARR	x	FFG	COMBAT	4	r11	0	0	0	1	0	0
SSN 717	OLYMPIA	x	SSN	COMBAT	1	r16	0	0	0	0	0	0
SSN 718	HONOLULU	x	SSN	COMBAT	6	r7	0	0	1	0	0	0
SSN 752	PASADENA	x	SSN	COMBAT	1	r12	0	0	1	0.5	1	0

Table 13. List of ships used (1 of 2)

Ship	Name	Avail	Class	Type	Start Day	Start Region	MIO	MCM	Mine	Intel	SubIntel
CG 58	PHILIPPINE SEA	x	CG	COMBAT	7	r10	1	0	0	1	0
CG 61	MONTEREY	x	CG	COMBAT	1	r2	1	0	0	1	0
CG 66	HUE CITY	x	CG	COMBAT	1	r13	1	0	0	1	0
CG 72	VELLA GULF	x	CG	COMBAT	4	r7	1	0	0	1	0
DDG 53	JOHN PAUL JONES	x	DDG	COMBAT	1	r1	1	0	0	1	0
DDG 62	FITZGERALD	x	DDG	COMBAT	1	r4	1	0	0	1	0
DDG 80	ROOSEVELT	x	DDG	COMBAT	4	r5	1	0	0	1	0
DDG 86	SHOUP	x	DDG	COMBAT	1	r9	1	0	0	1	0
DDG 90	CHAFEE	x	DDG	COMBAT	1	r7	1	0	0	1	0
DDG 97	HALSEY	x	DDG	COMBAT	7	r11	1	0	0	1	0
DDG 100	KIDD	x	DDG	COMBAT	4	r13	1	0	0	1	0
DDG 104	STERETT	x	DDG	COMBAT	4	r4	1	0	0	1	0
FFG 47	NICHOLAS	x	FFG	COMBAT	7	r8	1	0	0	1	0
FFG 48	VANDEGRIFT	x	FFG	COMBAT	4	r10	1	0	0	1	0
FFG 52	CARR	x	FFG	COMBAT	4	r11	1	0	0	1	0
SSN 717	OLYMPIA	x	SSN	COMBAT	1	r16	0	0	1	0	1
SSN 718	HONOLULU	x	SSN	COMBAT	6	r7	0	0	1	0	1
SSN 752	PASADENA	x	SSN	COMBAT	1	r12	0	0	1	0	1

Table 14. List of ships used (2 of 2)

C. OPERATIONAL SCENARIO

The base scenario contains 18 ships and 80 missions, which are subject to sixteen different regions throughout a 15-day planning window. There are eleven possible mission types; Air Defense (AD), Theater Ballistic Missile Defense (TBMD), Anti-Submarine Warfare (ASW), Anti-Surface Warfare (SUW), Precision Offensive Strike Missions (Strike), Naval Surface Fires Support (NSFS), Maritime Interdiction Operations (MIO), Mine Countermeasures (MCM), Offensive Mine Laying (Mine), Intelligence Gathering (Intel), and Submarine Intelligence Gathering (SubIntel). A full description of each mission area is described in Appendix B. With every day of a mission counting as an opportunity to gather value for that mission, the 80 missions converted into 623 tuples, each with a value to be gathered. Each ship is given a start day and a start region. This was determined to be the best course of action for realism when planning for operations. All units would not start at the same point or necessarily at the same time for an operation in the real world, so the model was set up to replicate reality.

The scenario for the Navy Mission Planner is intentionally designed with “holes” in the data; there are days with no missions, and there are regions with no missions. This is done to test the exploration limits of the heuristic, specifically to make sure it does not get stuck if it cannot “see” any nearby missions as it explores the regions.

1. Objective Function Value

The result of this research produces a few different outputs. The first output is the list of ships with their assigned schedules. Then, the primary missions and secondary missions for each ship in each region on each day are listed. Next in the output file is the list of all the possible missions with an indication of the completion of that mission. The final output produced is the value of the objective function. The objective function in this research is the sum of all the missions accomplished. These missions are defined by type, region, and day, and if feasible, are assigned to a ship for completion. The maximum value, being all missions are completed for every day, is 4292. This research produced a result of 3147. That amounts to 73% of the total value possible.

Table 15 and 16 below lists the ships used in this research, its start day, start region, and the schedule calculated for each ship. Days before the start day for each ship are marked with an "x." Other symbols seen in the table below are "T," which designates a travel day, and "0," which designates a day of zero value. The heuristic takes a day of zero value if there is no value to gain in the nearby regions. The heuristic may travel to another region if the value is greater in that distant region, or if there is no value that the heuristic can pick up before the last planning day, it terminates the schedule for that ship. A travel day is annotated in the output file by not listing a region for that day, since it will not place a ship in that region.

Ship	Name	Start Day	Start Region	d1	d2	d3	d4	d5	d6	d7	d8
CG 58	PHILIPPINE SEA	7	r10	x	x	x	x	x	x	r10	r12
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r7	r7	r7	r7
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13	r13
CG 72	VELLA GULF	4	r7	x	x	x	r7	r7	r7	r7	r7
DDG 53	JOHN PAUL JONES	1	r1	r1	r2	r2	r1	T	r7	r7	r7
DDG 62	FITZGERALD	1	r4	r4	r2	r2	r4	r7	r7	r7	r7
DDG 80	ROOSEVELT	4	r5	x	x	x	r5	r5	r5	r5	r5
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r10	r10	T	r13
DDG 90	CHAFEE	1	r7	r7	r2	r2	r3	r5	r5	r5	r5
DDG 97	HALSEY	7	r11	x	x	x	x	x	x	r11	r13
DDG 100	KIDD	4	r13	x	x	x	r13	r13	r13	r13	r13
DDG 104	STERETT	4	r4	x	x	x	r4	r5	r5	r5	r5
FFG 47	NICHOLAS	7	r8	x	x	x	x	x	x	r8	r8
FFG 48	VANDEGRIFT	4	r10	x	x	x	r10	r12	r11	r12	r10
FFG 52	CARR	4	r11	x	x	x	r11	r12	r11	r12	T
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16	r16
SSN 718	HONOLULU	6	r7	x	x	x	x	x	r7	r7	r7
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r10	r12	r10

Table 15. List of ships schedules (1 of 2)

Ship	Name	Start Day	Start Region	d9	d10	d11	d12	d13	d14	d15
CG 58	PHILIPPINE SEA	7	r10	r11	r13	r13	r13	r13	r13	r13
CG 61	MONTEREY	1	r2	r7	r7	r7	r2	r2	r2	r2
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13
CG 72	VELLA GULF	4	r7	r7	r7	r7	r2	r2	r2	r2
DDG 53	JOHN PAUL JONES	1	r1	r7	r7	r7	r2	r2	r2	r2
DDG 62	FITZGERALD	1	r4	r7	r7	r7	r2	r2	r2	r2
DDG 80	ROOSEVELT	4	r5	r5	r5	T	r2	r2	r2	r2
DDG 86	SHOUP	1	r9	r13	r13	r11	r12	r12	r12	r12
DDG 90	CHAFEE	1	r7	r5	r5	r8	r5	r4	r2	r2
DDG 97	HALSEY	7	r11	r13	r13	r11	r12	r12	r12	r12
DDG 100	KIDD	4	r13	r13	r13	r12	r12	r12	r12	r12
DDG 104	STERETT	4	r4	r5	r5	r8	r5	T	r2	r2
FFG 47	NICHOLAS	7	r8	r8	r8	r8	r5	r8	r8	r8
FFG 48	VANDEGRIFT	4	r10	T	r13	r12	0	0	0	0
FFG 52	CARR	4	r11	r13	T	r12	0	0	0	0
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16
SSN 718	HONOLULU	6	r7	r7	r7	r7	0	0	0	0
SSN 752	PASADENA	1	r12	r13	T	r12	0	0	0	0

Table 16. List of ships schedules (2 of 2)

D. ANALYSIS AND COMPARISON

In order to ascertain whether this research produces an improvement to the mission planning process, the output is compared to different outputs, included the latest update to the formulation of NMP in which the results were produced by GAMS, using the information provided in Silva 2009.

1. Other Potential Solutions

This research uses the same list of ships, ensuring consistency during development. The ships' start regions, start days, and order in the stack (alphabetically by ship class then numerically by hull number) are unchanged while in development. To determine the best feasible solution, after the research is stabilized, the stack order is modified. Eight variations were tested. A description of each test with the value achieved is listed below. The routes chosen by these methods of ship order are displayed in Appendix D.

- Alphabetical by ship class, then numerical by hull number (original list) - 3147
- Reverse alphabetical, reverse numerical (reversed ship order) - 2754
- Alphabetical by ship name - 2808
- Reverse alphabetical by ship name - 2639
- By earliest start day, then alphabetical by ship class, then numerical by hull number - 2971
- By latest start day, then alphabetical by ship class, then numerical by hull number - 2900
- By lowest numbered start region, then alphabetical by ship class, then numerical by hull number - 3110
- By highest numbered start region, then alphabetical by ship class, then numerical by hull number - 2839

2. GAMS Solution

Using GAMS, the current formulation produces a feasible result of 3115, which is 72.58% of the total value possible. The heuristic in this research produces a result of 3147, only 73.32%. The 0.74% difference could mean the difference between the GAMS optimal solution and closing the gap to the problem optimal solution. The reason for a

gap between the two solutions is based upon the different approaches. GAMS uses brute force enumeration while this research focuses on a greedy heuristic. With limitation on the enumeration, the heuristic was able to produce certain routes that could not be enumerated in the allotted memory. Tables 17 and 18 are formatted in the same manner as the solution above, but will show the routes generated from the latest formulation ran through GAMS.

Ship	Name	Start Day	Start Region	d1	d2	d3	d4	d5	d6	d7
CG 58	PHILIPPINE SEA	7	r10	x	x	x	x	x	x	r10
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13
CG 72	VELLA GULF	4	r7	x	x	x	r7	r7	r7	r7
DDG 53	JOHN PAUL JONES	1	r1	r1	r1	r1	r1	r2	r2	r2
DDG 62	FITZGERALD	1	r4	r4	r4	r4	r4	r4	r4	r4
DDG 80	ROOSEVELT	4	r5	x	x	x	r5	r5	r5	r5
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r9	r9	r9
DDG 90	CHAFEE	1	r7	r7	r7	r7	r7	r7	r7	r7
DDG 97	HALSEY	7	r11	x	x	x	x	x	x	r11
DDG 100	KIDD	4	r13	x	x	x	r13	r13	r13	r13
DDG 104	STERETT	4	r4	x	x	x	r4	r4	r4	r4
FFG 47	NICHOLAS	7	r8	x	x	x	x	x	x	T
FFG 48	VANDEGRIFT	4	r10	x	x	x	r10	0	0	r10
FFG 52	CARR	4	r11	x	x	x	r11	0	0	r11
SSN 717	OLYMPIA	1	r16	0	r16	r16	r16	r16	r16	r16
SSN 718	HONOLULU	6	r7	x	x	x	x	x	r7	r7
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	T

Table 17. List of GAMS generated Routes (1 of 2)

Ship	Name	Start Day	Start Region	d8	d9	d10	d11	d12	d13	d14	d15
CG 58	PHILIPPINE SEA	7	r10	r10	r10	T	r11	r11	r11	r11	r11
CG 61	MONTEREY	1	r2	r2	r2	r3	r3	r3	r3	r3	r4
CG 66	HUE CITY	1	r13	r13	r13	T	T	T	T	r2	r2
CG 72	VELLA GULF	4	r7	r7	r7	T	r8	r8	r8	r8	r5
DDG 53	JOHN PAUL JONES	1	r1	r2	r2	r2	r2	r2	r2	r3	r2
DDG 62	FITZGERALD	1	r4	r4	r4	r5	r5	r5	r5	r5	r5
DDG 80	ROOSEVELT	4	r5	r5	r5	T	r7	r7	r7	r7	r7
DDG 86	SHOUP	1	r9	r9	r9	r10	r10	r10	r10	r10	r10
DDG 90	CHAFEE	1	r7	r7	r7	T	r8	r8	r8	r8	r9
DDG 97	HALSEY	7	r11	r11	r11	r13	r13	r13	r13	r13	r13
DDG 100	KIDD	4	r13	r13	r13	T	T	T	T	r2	r7
DDG 104	STERETT	4	r4	r4	r4	r5	r5	r5	r5	r5	r8
FFG 47	NICHOLAS	7	r8	T	T	T	T	r12	r12	r12	r10
FFG 48	VANDEGRIFT	4	r10	r10	r12	r12	r12	T	T	r13	r13
FFG 52	CARR	4	r11	r11	r11	T	T	r13	r13	r13	r13
SSN 717	OLYMPIA	1	r16	r16	r16	0	0	0	0	0	0
SSN 718	HONOLULU	6	r7	r7	r7	T	T	r10	r10	r10	r12
SSN 752	PASADENA	1	r12	T	T	T	r16	r16	r16	r16	r16

Table 18. List of GAMS generated Routes (2 of 2)

3. Heuristic and GAMS Analysis

The difference between the values of each approach is less than 1% of the total value possible. Each approach however is very unique. The enumeration of the routes as done in the GAMS base solution reached the limit of memory before it was able to reach more diversified routes and conduct its exploration from there. The diversity in the routes generated by the heuristic allowed Excel to create paths that GAMS had not had a chance to explore. The heuristic created paths would have taken complete enumeration for GAMS to find, and since the graph consists of 15 planning days and 16 different regions would take over two billion years to calculate if a computer could create one hundred routes per second, every second. The greedy heuristic proves to be a better route generator, but does not generate a proven optimal solution.

E. CONCLUSION AND FURTHER RESEARCH

Future research on NMP should include integrating the heuristic researched here into the optimization model from Silva (2009). The paths built by our heuristic would provide a good starting solution for those models. The heuristic routes generated cover more of enumerated paths than GAMS could have covered. Another research avenue should be in various route generation methods. Brute force enumeration, even with a defined solution starting point, would not cover enough of the paths to provide an optimal solution. Other generation methods, possibly not based on depth-first enumeration, may prove able to obtain a better, if not optimal, solution. Additionally, the sequence in which ships are considered plays a very important role in our heuristic algorithm. We processed the ships in alphabetical order, first by ship class and then by hull number, Ship sequence was not thoroughly researched and further effort on the importance of ship order could prove valuable for operational planners.

The next phase of research for NMP would be to analyze the paths generated against real world scenarios, whether historic or current. The evaluation of the suggestions from the model and the comparisons to the plans could have an effect on future planning. Also, this research used academic assumptions about the limitations of ships and systems. Updating the model with real world capabilities and limitations is straightforward, and would certainly provide more relevant solutions.

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APPENDIX A

A. USE OF NMP FORMULATION

The following is the formulation of the Navy Mission Planner as published in Silva (2009). It is used as reference for the base formulation of NMP. It is copied into section B without modification (Silva, 2009, chapter III, section C).

B NMP INTEGER PROGRAM FORMULATION

Many of the inputs to NMP are unchanged, but this research significantly changes the formulation of model. The following integer linear program solves for the optimal set of Navy ship employment schedules.

1. Sets and Indices [cardinality]

$s \in S$ Ship (hull number and name, alias *s'*) [~50]

$m \in M$ Mission type (alias *m'*) [~10] (e.g., AD, MIO, Intel, TBMD)

$c \in C_s$ Concurrent mission capability set for ship *s* [~10]

$m \in M_c$ Mission types in concurrent (simultaneous) mission set *c*

(e.g., ship *s* can simultaneously perform mission type *m* in concurrent mission capability set *c*.)

$p \in P$ Employment schedules [~1 million]

$p \in P_s \subseteq P$ Employment schedules for ship *s* [~1 million]

($\bigcup_s P_s \equiv P, P_s$ is a partition of *P*.)

$s(p)$ Ship of employment schedule *p*

$r \in R$ Regions in AOR [~30]

$d \in D$ Days in planning horizon (alias *d'*, *d''*) [~14]

$r(p,d)$ Region employment schedule p visits on day d

$n \in N$ Ordinal for multiple missions of the same mission type [~5]

(e.g., several ships may conduct ASW at the same time within the same region, but with different effectiveness.)

2. Data [units]

$value_{m,n,r,d}$ Priority of n-th mission of type m, in region r on day d [1–20]

[value] $\{m,n,r,d\} \in MNRD$ tuples exist only for non-zero values)

$accomplish_{c,m}$ Level of accomplishment of concurrent mission set $c \in C_s$, mission $m \in M_c$ [0.0 - 1.0] (Note that each ship may have its own set of concurrent mission capability sets, and that some of these sets may contain the same missions, but with different accomplish rates to represent the ship choosing to change emphasis between missions.)

3. Induced Index Sets

$\{m,n,r,d\} \in MNRD$ 4-tuple exists only if value *m, n, r, d* > 0 or accomplish *s,m* >0 for some ship that can employ a concurrent mission capability set that includes mission *m* in region *r* on day *d*

$\{m,r,d\} \in MRD$ 3-tuple exists only if $\{m,n,r,d\} \in MNRD$ does for some *n*

$\{m,r,d,m'\} \in MRDM$ 4-tuple exists if, in region *r* on day *d*, mission *m* can be undertaken only if mission *m'* is fully accomplished

4. Variables [units]

$U_{m,n,r,d}$ Level of accomplishment of the *n*-th mission type *m* assignment

in region r on day d [0.0–1.0]

$V_{m,r,d}$ =1 if mission m is fully accomplished in region r on day d [binary]

$W_{s,c,d,r}$ =1 if ship s employs concurrent mission capability c on day d in region r [binary]

$X_{s,s',r,d}$ =1 only if ships s and s' are both in region r on day d [binary]

Y_p =1 if schedule p is selected [binary]

5. Formulation

$$\max \sum_{\{m,n,r,d\}\in MNRD} value_{m,n,r,d} U_{m,n,r,d} \qquad \text{(T0)}$$

s.t.

$$\sum_{p\in P_s} Y_p = 1 \qquad \forall s \in S \qquad \text{(T1)}$$

$$\sum_{c\in C_s} W_{s,c,d,r} \le \sum_{\substack{p\in P_s \\ \wedge \exists r(p,d)}} Y_p \qquad \forall s \in CS, d \in D, r \in R \qquad \text{(T2)}$$

$$\sum_{n|\{m,n,r,d\}\in MNRD} U_{m,n,r,d} \le \sum_{s,c\in C_s} accomplish_{c,m} W_{s,c,d,r}$$

$$\forall \{m,r,d\} \in MRD \qquad \text{(T3)}$$

$$V_{m,r,d} \le \sum_{\substack{p\in P \| r=r(p,d) \\ \wedge c\in C_{s(p)} \wedge m\in M_c}} accomplish_{c,m} Y_p \qquad \forall \{m,r,d\} \in MRD \qquad \text{(T4)}$$

$$V_{m,r,d} \le \sum_{n|\{m,n,r,d\}\in MNRD} U_{m,n,r,d} \qquad \forall \{m,r,d\} \in MRD \qquad \text{(T4a)}$$

$$U_{m,n,r,d} \le V_{m',r,d} \qquad \forall m,n,r,d \,\big|\, \{m,n,r,d\} \in MNRD$$

$$\wedge \{m,r,d,m'\} \in MRDM \qquad \text{(T5)}$$

$$U_{m,n,r,d} \in [0,1] \qquad \forall \{m,n,r,d\} \in MNRD$$

$$V_{m,r,d} \in \{0,1\} \qquad \forall \{m,r,d) \in MRD$$

$$W_{s,c,d,r} \in \{0,1\} \qquad \forall s \in S, c \in C_s, d \in D, r \in R$$

$$Y_p \in \{0,1\} \qquad \forall p \in P$$

6. Discussion

The objective (T0) sums the total value of completed and partially completed missions. Each packing constraint (T1) allows exactly one employment schedule per ship. Each constraint (T2) permits a combatant to employ a concurrent mission capability on a given day only if an employment schedule exists for that ship. Each constraint (T3) limits the sum of the partial completion values of all missions by the total mission accomplishment for every tuple of mission, region, and day. Each constraint (T4) assigns full accomplishment to a mission in a particular region on a particular day only if there is at least one total unit of accomplishment for that same combination of mission, region, and day. Similarly, each constraint (T4a) assigns full accomplishment to a mission in a particular region on a particular day only if each mission copy combines in that region on that day to produce at least one total unit of accomplishment. Constraints T4 and T4a are equivalent for determining optimal employment schedules, *Y*, but T4a enforces additional structure on the individual mission accomplishment variables, *U*, for prerequisite missions that have no prescribed value. Each constraint (T5) ensures that no mission accrues accomplishment in a given region on a given day unless each of its prerequisite missions (if any) in that region on that day has full accomplishment. (T6) defines the variable domains.

APPENDIX B

A. USE OF MISSION TYPE DEFINITION

The following is the definition of the mission types as published in Silva (2009). It is used as reference for the mission types used in this research. It is copied into part 1 without modification (Silva 2009, chapter IV, section A, part 1).

B. MISSION TYPES

Dugan (2007) applies ten mission types and two supporting mission types in NMP. We modify the NMP mission set to include eleven mission types and delete the supporting mission types Transit and Off-Station. NMP handles transit and off-station time within the underlying VBA code.

While representative of the most common maritime missions, our list of mission types is not intended to be exhaustive. The operational planner may define any mission type necessary to suit the commander’s objectives. NMP accepts any mission name on the *Missions* worksheet.

Acronyms or abbreviations in parenthesis denote NMP notation. Joint Publication 1–02 (2001) defines the following, except as otherwise noted:

1. Air Defense (AD)

Defensive measures designed to destroy attacking enemy aircraft or missiles in the atmosphere, or to nullify or reduce the effectiveness of such attack. (JP 1–02 2001)

We consider air defense separately from missile defense.

2. Theater Ballistic Missile Defense (TBMD)

A ballistic missile is:

> Any missile which does not rely upon aerodynamic surfaces to produce lift and consequently follows a ballistic trajectory when thrust is terminated (JP 1–02 2001).

Missile defense is:

> Defensive measures designed to destroy attacking enemy missiles, or to nullify or reduce the effectiveness of such attack (JP 1–02 2001).

We use the term TBMD to describe the naval mission of providing ballistic missile defense to a theater of operations.

3. Antisubmarine Warfare (ASW)

Operations conducted with the intention of denying the enemy the effective use of submarines (JP 1–02 2001).

4. Surface Warfare (SUW)

That portion of maritime warfare in which operations are conducted to destroy or neutralize enemy naval surface forces and merchant vessels (JP 1–02 2001).

5. Strike

An attack to damage or destroy an objective or a capability. (JP 1–02 2001). Naval fire resources are sea based or sea supported, and include Navy and Marine Corps lethal and nonlethal air-delivered weapons, maritime-based gunfire and land-attack missiles, and maritime-based naval special warfare units (NWP 3–09.1 2005).

6. Naval Surface Fire Support (NSFS)

Fire provided by Navy surface gun and missile systems in support of a unit or units (JP 1–02, 2001).

7. Maritime Interception Operations (MIO)

Efforts to monitor, query, and board merchant vessels in international waters to enforce sanctions against other nations such as those in support of United Nations Security Council Resolutions and/or prevent the transport of restricted goods (JP 1–02 2001).

8. Mine Countermeasures (MCM)

All methods for preventing or reducing damage or danger from mines (JP 1–02 2001).

9. Mine Warfare (Mine)

The strategic, operational, and tactical use of mines and mine countermeasures. Mine warfare is divided into two basic subdivisions: the laying of mines to degrade the enemy's capabilities to wage land, air, and 23 maritime warfare; and the countering of enemy-laid mines to permit friendly maneuver or use of selected land or sea areas (JP 1–02 2001).

10. Intelligence Collection (Intel)

The collection of available information concerning foreign nations, hostile or potentially hostile forces or elements, or areas of actual or potential operations (JP 1–02 2001).

11. Submarine Intelligence Collection (SubIntel)

The previous ten mission types are also used in Dugan (2007). We have added SubIntel, a user-defined mission, to illustrate the flexibility of this planning tool through its ability to adapt to *any* list of mission types. We define SubIntel as an intelligence collection mission that can only be performed by a submarine.

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APPENDIX C

A. MISSION LIST

Below is the list of missions used in the calculations of this research. The value associated with each mission is based on a priority listed determined by the Commander during planning on a scale from 1 to 20. The missions with the highest importance are assigned higher values.

Mission	Include	Type	Region	Start Day	End Day	Value	Requires	
m1	x	MIO	r1	1	4	9	AD	
m2	x	AD	r1	1	4	7		
m3	x	ASW	r1	1	4	8	AD	SUW
m4	x	Intel	r1	1	4	7		
m5	x	TBMD	r2	1	15	20	AD	
m6	x	MIO	r3	1	4	5	AD	
m7	x	AD	r3	1	15	3		
m8	x	ASW	r3	1	4	4	AD	
m9	x	Intel	r3	1	15	3		
m10	x	MIO	r4	1	4	7	AD	
m11	x	AD	r4	1	15	5		
m12	x	ASW	r4	1	4	6	SUW	
m13	x	Intel	r4	1	15	5		
m14	x	Strike	r4	5	11	7	AD	
m15	x	NSFS	r4	5	8	5	AD	
m16	x	SUW	r4	5	11	5	AD	
m17	x	MIO	r4	12	15	3	AD	
m18	x	ASW	r4	12	15	3	SUW	
m19	x	MIO	r5	1	4	5	AD	
m20	x	AD	r5	1	15	3		
m21	x	ASW	r5	1	4	4	SUW	
m22	x	Intel	r5	1	15	3		
m23	x	Strike	r5	5	11	15	AD	
m24	x	NSFS	r5	5	8	7	AD	
m25	x	SUW	r5	5	11	7	AD	
m26	x	MIO	r5	12	15	5	AD	
m27	x	ASW	r5	12	15	5	SUW	
m28	x	MIO	r7	1	4	9	AD	
m29	x	AD	r7	1	15	7		
m30	x	ASW	r7	1	15	8	AD	
m31	x	Intel	r7	1	15	7		SUW
m32	x	Strike	r7	5	11	15	AD	
m33	x	NSFS	r7	5	8	7	AD	
m34	x	SUW	r7	5	11	7	AD	
m35	x	MIO	r7	12	15	5	AD	
m36	x	ASW	r7	12	15	5	SUW	
m37	x	MIO	r8	1	4	5	AD	
m38	x	AD	r8	1	15	3		
m39	x	ASW	r8	1	4	4	SUW	
m40	x	Intel	r8	1	15	3		

Table 19. List of missions in NMP (1 of 2)

Mission	Include	Type	Region	Start Day	End Day	Value	Requires	
m41	x	Strike	r8	5	11	5	AD	
m42	x	NSFS	r8	5	8	3	AD	
m43	x	SUW	r8	5	11	3	AD	
m44	x	MIO	r9	1	4	7	AD	
m45	x	AD	r9	1	15	5		
m46	x	ASW	r9	1	4	6	SUW	
m47	x	Intel	r9	1	15	5		
m48	x	Strike	r9	5	11	5	AD	
m49	x	NSFS	r9	5	8	3	AD	
m50	x	SUW	r9	5	11	3	AD	
m51	x	MIO	r10	1	4	5	AD	
m52	x	AD	r10	1	15	3		
m53	x	ASW	r10	1	4	4	SUW	
m54	x	Intel	r10	1	15	3		
m55	x	Strike	r10	5	11	7	AD	
m56	x	NSFS	r10	5	8	5	AD	
m57	x	SUW	r10	5	11	5	AD	
m58	x	MIO	r10	12	15	3	AD	
m59	x	ASW	r10	12	15	3	SUW	
m60	x	MIO	r11	1	4	7	AD	
m61	x	AD	r11	1	15	5		
m62	x	ASW	r11	1	4	6	SUW	
m63	x	Intel	r11	1	15	5		
m64	x	Strike	r11	5	11	7	AD	
m65	x	NSFS	r11	5	8	5	AD	
m66	x	SUW	r11	5	11	5	AD	
m67	x	MIO	r11	12	15	3	AD	
m68	x	ASW	r11	12	15	3	SUW	
m69	x	ASW	r12	1	15	20		
m70	x	MIO	r13	1	4	9	AD	
m71	x	AD	r13	1	15	7		
m72	x	ASW	r13	1	15	8	AD	
m73	x	Intel	r13	1	15	7		SUW
m74	x	Strike	r13	5	11	15	AD	
m75	x	NSFS	r13	5	8	7	AD	
m76	x	SUW	r13	5	11	7	AD	
m77	x	MIO	r13	12	15	5	AD	
m78	x	ASW	r13	12	15	5	SUW	
m79		AD	r2	1	15	20		
m80	x	SubIntel	r16	2	15	20		

Table 20. List of missions in NMP (2 of 2)

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APPENDIX D

A. ALTERNATIVE SHIP ORDERS

The tables below are alternative ordering of the ships used in this research. Each table was valued less than the original model, as stated in chapter four, section B, subsection 1 on page 29. These tables presented show the various paths created by the heuristic and show the differences based solely on ship order through the heuristic.

Ship	Name	Start Day	Start Region	d1	d2	d3	d4	d5	d6	d7	d8
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	r12	r12
SSN 718	HONOLULU	6	r7	x	x	x	x	x	r7	r7	r7
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16	r16
FFG 52	CARR	4	r11	x	x	x	r11	r13	r13	r13	r13
FFG 48	VANDEGRIFT	4	r10	x	x	x	r10	r12	r12	r12	r12
FFG 47	NICHOLAS	7	r8	x	x	x	x	x	x	r8	r5
DDG 104	STERETT	4	r4	x	x	x	r4	r7	r7	r7	r7
DDG 100	KIDD	4	r13	x	x	x	r13	r13	r13	r13	r13
DDG 97	HALSEY	7	r11	x	x	x	x	x	x	r11	r13
DDG 90	CHAFEE	1	r7	r7	r2	r2	r2	r7	r7	r7	r7
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r9	r9	r9	r9
DDG 80	ROOSEVELT	4	r5	x	x	x	r5	r5	T	r2	r2
DDG 62	FITZGERALD	1	r4	r4	r2	r2	r2	r2	r2	r2	r2
DDG 53	JOHN PAUL JONES	1	r1	r1	r2	r2	r2	r2	r2	r2	r2
CG 72	VELLA GULF	4	r7	x	x	x	r7	r2	r2	r2	r2
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13	r13
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2	r2
CG 58	PHILIPPINE SEA	7	r10	x	x	x	x	x	x	r10	r12

Table 21. Reverse Ship Order (Table 1 of 2)

Ship	Name	Start Day	Start Region	d9	d10	d11	d12	d13	d14	d15
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	r12
SSN 718	HONOLULU	6	r7	r7	r7	r7	r7	r7	r7	r7
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16
FFG 52	CARR	4	r11	r13	r13	r13	r13	r13	r13	r13
FFG 48	VANDEGRIFT	4	r10	r12	r12	r12	r12	r12	r12	r12
FFG 47	NICHOLAS	7	r8	r4	r7	r7	r7	r7	r7	r7
DDG 104	STERETT	4	r4	r7	r7	r7	r2	r2	r2	r2
DDG 100	KIDD	4	r13	r13	r13	r13	r13	r13	r13	r13
DDG 97	HALSEY	7	r11	r13	r13	r13	r13	r13	r13	r13
DDG 90	CHAFEE	1	r7	r7	r7	r7	r2	r2	r2	r2
DDG 86	SHOUP	1	r9	T	r5	r5	T	r2	r2	r2
DDG 80	ROOSEVELT	4	r5	r7	r7	r2	r2	r2	r2	r2
DDG 62	FITZGERALD	1	r4	r7	r7	r2	r2	r2	r2	r2
DDG 53	JOHN PAUL JONES	1	r1	r7	T	r5	r5	T	r2	r2
CG 72	VELLA GULF	4	r7	r7	T	r5	r5	r5	r5	r5
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13
CG 61	MONTEREY	1	r2	r7	T	T	r2	r2	r2	r2
CG 58	PHILIPPINE SEA	7	r10	r12	r12	r12	r12	r12	r12	r12

Table 22. Reverse Ship Order (Table 2 of 2)

Ship	Name	Start Day	Start Region	d1	d2	d3	d4	d5	d6	d7	d8
FFG 52	CARR	4	r11	x	x	x	r11	r12	r12	r12	r12
DDG 90	CHAFEE	1	r7	r7	r2	r2	r2	r7	r7	r7	r7
DDG 62	FITZGERALD	1	r4	r4	r2	r2	r2	r2	r2	r2	r2
DDG 97	HALSEY	7	r11	x	x	x	x	x	x	r11	r13
SSN 718	HONOLULU	6	r7	x	x	x	x	x	r7	r7	r7
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13	r13
DDG 53	JOHN PAUL JONES	1	r1	r1	r2	r2	r2	r2	r2	r2	r2
DDG 100	KIDD	4	r13	x	x	x	r13	r13	r13	r13	r13
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2	r2
FFG 47	NICHOLAS	7	r8	x	x	x	x	x	x	r8	r5
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16	r16
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	r10	r12
CG 58	PHILIPPINE SEA	7	r10	x	x	x	x	x	x	r10	r10
DDG 80	ROOSEVELT	4	r5	x	x	x	r5	r5	r5	r5	T
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r10	r9	r9	T
DDG 104	STERETT	4	r4	x	x	x	r4	r2	r2	r2	r2
FFG 48	VANDEGRIFT	4	r10	x	x	x	r10	r12	r10	T	r12
CG 72	VELLA GULF	4	r7	x	x	x	r7	r2	r2	r2	r2

Table 23. Ship Order by Ship Name Alphabetically (Table 1 of 2)

Ship	Name	Start Day	Start Region	d9	d10	d11	d12	d13	d14	d15
FFG 52	CARR	4	r11	r12	r12	r12	r12	r12	r12	r12
DDG 90	CHAFEE	1	r7	r7	r7	r7	r2	r2	r2	r2
DDG 62	FITZGERALD	1	r4	r2	r2	r2	r2	r2	r2	r2
DDG 97	HALSEY	7	r11	r13	r13	r13	r13	r13	r13	r13
SSN 718	HONOLULU	6	r7	r7	r7	r7	r7	r7	r7	r7
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13
DDG 53	JOHN PAUL JONES	1	r1	r2	r2	r2	r2	r2	r2	r2
DDG 100	KIDD	4	r13	r13	r13	r13	r13	r13	r13	r13
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2
FFG 47	NICHOLAS	7	r8	r5	r5	r5	r5	r5	r5	r5
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	r12
CG 58	PHILIPPINE SEA	7	r10	r9	r9	r9	r9	r9	r9	r9
DDG 80	ROOSEVELT	4	r5	r2	r2	r2	r2	r2	r2	r2
DDG 86	SHOUP	1	r9	r5	r5	r5	r5	r5	r5	r5
DDG 104	STERETT	4	r4	r2	r2	r2	r2	r2	r2	r2
FFG 48	VANDEGRIFT	4	r10	0	r12	r12	r12	r12	r12	r12
CG 72	VELLA GULF	4	r7	r2	r2	0	r2	r2	r2	0

Table 24. Ship Order by Ship Name Alphabetically (Table 2 of 2)

Ship	Name	Start Day	Start Region	d1	d2	d3	d4	d5	d6	d7	d8
CG 72	VELLA GULF	4	r7	x	x	x	r7	r7	r7	r7	r7
FFG 48	VANDEGRIFT	4	r10	x	x	x	r10	r12	r12	r12	r12
DDG 104	STERETT	4	r4	x	x	x	r4	r2	r2	r2	r2
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r9	r9	r9	r9
DDG 80	ROOSEVELT	4	r5	x	x	x	r5	r5	r5	r5	r5
CG 58	PHILIPPINE SEA	7	r10	x	x	x	x	x	x	r10	r12
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	r12	r12
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16	r16
FFG 47	NICHOLAS	7	r8	x	x	x	x	x	x	r8	r8
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2	r2
DDG 100	KIDD	4	r13	x	x	x	r13	r13	r13	r13	r13
DDG 53	JOHN PAUL JONES	1	r1	r1	r2	r2	r2	r2	r2	r2	r2
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13	r13
SSN 718	HONOLULU	6	r7	x	x	x	x	x	r7	r7	r7
DDG 97	HALSEY	7	r11	x	x	x	x	x	x	r11	r13
DDG 62	FITZGERALD	1	r4	r4	r2	r2	r2	r2	r2	r2	r2
DDG 90	CHAFEE	1	r7	r7	r2	r2	r2	r2	r2	r2	r2
FFG 52	CARR	4	r11	x	x	x	r11	r12	r12	r12	r12

Table 25. Ship Order by Ship Name Reversed Alphabetically (Table 1 of 2)

Ship	Name	Start Day	Start Region	d9	d10	d11	d12	d13	d14	d15
CG 72	VELLA GULF	4	r7	r7	r7	r7	r2	r2	r2	r2
FFG 48	VANDEGRIFT	4	r10	r12	r12	r12	r12	r12	r12	r12
DDG 104	STERETT	4	r4	r2	r2	r2	r2	r2	r2	r2
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r9	r9	r9
DDG 80	ROOSEVELT	4	r5	r5	r5	r5	T	r2	r2	r2
CG 58	PHILIPPINE SEA	7	r10	T	r13	r13	r13	r13	r13	r13
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	r12
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16
FFG 47	NICHOLAS	7	r8	r8	r8	r8	r5	r5	r5	r5
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2
DDG 100	KIDD	4	r13	r13	r13	r13	r13	r13	r13	r13
DDG 53	JOHN PAUL JONES	1	r1	r2	r2	r2	r2	r2	r2	r2
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13
SSN 718	HONOLULU	6	r7	r7	r7	r7	T	T	T	r12
DDG 97	HALSEY	7	r11	r13	r13	r13	r13	r13	r13	r13
DDG 62	FITZGERALD	1	r4	r2	r2	r2	r2	r2	r2	r2
DDG 90	CHAFEE	1	r7	r2	r2	r2	r2	r2	r2	r2
FFG 52	CARR	4	r11	r12	r12	r12	r12	r12	r12	r12

Table 26. Ship Order by Ship Name Reversed Alphabetically (Table 2 of 2)

Ship	Name	Start Day	Start Region	d1	d2	d3	d4	d5	d6	d7	d8
DDG 53	JOHN PAUL JONES	1	r1	r1	r1	r2	r2	r7	r7	r7	r7
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r7	r7	r7	r7
DDG 62	FITZGERALD	1	r4	r4	r2	r2	T	r7	r7	r7	r7
DDG 104	STERETT	4	r4	x	x	x	r4	r7	r7	r7	r7
DDG 80	ROOSEVELT	4	r5	x	x	x	r5	r5	r5	r5	r5
DDG 90	CHAFEE	1	r7	r7	r2	r2	r7	r7	r7	r7	r7
CG 72	VELLA GULF	4	r7	x	x	x	r7	r7	r7	r7	r7
SSN 718	HONOLULU	6	r7	x	x	x	x	x	r7	r7	r7
FFG 47	NICHOLAS	7	r8	x	x	x	x	x	x	r8	r9
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r10	r10	r10	r10
FFG 48	VANDEGRIFT	4	r10	x	x	x	r10	r12	r11	r13	r13
CG 58	PHILIPPINE SEA	7	r10	x	x	x	x	x	x	r10	r13
FFG 52	CARR	4	r11	x	x	x	r11	r13	r13	r13	r13
DDG 97	HALSEY	7	r11	x	x	x	x	x	x	r11	r13
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r10	r13	r13
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13	r13
DDG 100	KIDD	4	r13	x	x	x	r13	r13	r13	r13	r13
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16	r16

Table 27. Ship Order by Start Region (Table 1 of 2)

Ship	Name	Start Day	Start Region	d9	d10	d11	d12	d13	d14	d15
DDG 53	JOHN PAUL JONES	1	r1	r7	r7	r7	r2	r2	r2	r2
CG 61	MONTEREY	1	r2	r7	r7	r7	r2	r2	r2	r2
DDG 62	FITZGERALD	1	r4	r7	r7	r7	r2	r2	r2	r2
DDG 104	STERETT	4	r4	r7	r7	r7	r2	r2	r2	r2
DDG 80	ROOSEVELT	4	r5	r5	r5	T	r2	r2	r2	r2
DDG 90	CHAFEE	1	r7	r7	r7	r7	r2	r2	r2	r2
CG 72	VELLA GULF	4	r7	T	r5	r8	r9	r10	r12	r12
SSN 718	HONOLULU	6	r7	r7	r7	r7	r7	0	0	0
FFG 47	NICHOLAS	7	r8	r9	r9	r9	r10	r12	r12	r12
DDG 86	SHOUP	1	r9	r12	r11	r13	r13	r13	r13	r13
FFG 48	VANDEGRIFT	4	r10	r13	r13	r13	r13	r13	r13	r13
CG 58	PHILIPPINE SEA	7	r10	r13	r13	r13	r13	r13	r13	r13
FFG 52	CARR	4	r11	r13	r13	r13	r13	r13	r13	r13
DDG 97	HALSEY	7	r11	r13	r13	r13	r13	r13	r13	r13
SSN 752	PASADENA	1	r12	r13	r13	r13	r13	r13	r13	r13
CG 66	HUE CITY	1	r13	r13	r13	r13	T	T	T	r8
DDG 100	KIDD	4	r13	r13	r13	r13	r13	r13	r13	r13
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16

Table 28. Ship Order by Start Region (Table 2 of 2)

Ship	Name	Start Day	Start Region	d1	d2	d3	d4	d5	d6	d7	d8
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16	r16
CG 66	HUE CITY	1	r13	r13	r13	r13	r11	r13	r13	r13	r13
DDG 100	KIDD	4	r13	x	x	x	r13	r13	r13	r13	r13
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r10	r12	r12	r12
FFG 52	CARR	4	r11	x	x	x	r11	r13	r11	r12	r12
DDG 97	HALSEY	7	r11	x	x	x	x	x	x	r11	r13
FFG 48	VANDEGRIFT	4	r10	x	x	x	r10	r9	r9	r9	r9
CG 58	PHILIPPINE SEA	7	r10	x	x	x	x	x	x	r10	r9
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r10	r10	T	r13
FFG 47	NICHOLAS	7	r8	x	x	x	x	x	x	r8	r5
DDG 90	CHAFEE	1	r7	r7	r2	r2	r2	r7	r7	r7	r7
CG 72	VELLA GULF	4	r7	x	x	x	r7	r2	r2	r2	r2
SSN 718	HONOLULU	6	r7	x	x	x	x	x	r7	r7	r7
DDG 80	ROOSEVELT	4	r5	x	x	x	r5	r5	r5	r5	r5
DDG 62	FITZGERALD	1	r4	r4	r2	r2	r2	r2	r2	r2	r2
DDG 104	STERETT	4	r4	x	x	x	r4	r2	r2	r2	r2
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2	r2
DDG 53	JOHN PAUL JONES	1	r1	r1	r2	r2	r2	r2	r2	r2	r2

Table 29. Ship Order by Reversed Start Region (Table 1 of 2)

Ship	Name	Start Day	Start Region	d9	d10	d11	d12	d13	d14	d15
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16
CG 66	HUE CITY	1	r13	r13	r13	r11	r12	r12	r12	r12
DDG 100	KIDD	4	r13	r13	r13	r13	r13	r13	r13	r13
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	r12
FFG 52	CARR	4	r11	r12	r12	r12	r12	r12	r12	r12
DDG 97	HALSEY	7	r11	r13	r13	r11	r12	r12	r12	r12
FFG 48	VANDEGRIFT	4	r10	r9	r9	r9	r10	r12	r12	r12
CG 58	PHILIPPINE SEA	7	r10	T	r5	r5	r4	r2	r2	r2
DDG 86	SHOUP	1	r9	r13	r13	r11	r12	r12	r12	r12
FFG 47	NICHOLAS	7	r8	r7	r7	r7	r7	r7	r7	r7
DDG 90	CHAFEE	1	r7	r7	r7	r7	r2	r2	r2	r2
CG 72	VELLA GULF	4	r7	r2	r2	r2	r2	r2	r2	r2
SSN 718	HONOLULU	6	r7	r7	r7	r7	r7	r7	r7	r7
DDG 80	ROOSEVELT	4	r5	r5	T	r2	r2	r2	r2	r2
DDG 62	FITZGERALD	1	r4	r2	r2	r2	r2	r2	r2	r2
DDG 104	STERETT	4	r4	r2	r2	r2	r2	r2	r2	r2
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2
DDG 53	JOHN PAUL JONES	1	r1	r2	r2	r2	r2	r2	r2	r2

Table 30. Ship Order by Reversed Start Region (Table 2 of 2)

Ship	Name	Start Day	Start Region	d1	d2	d3	d4	d5	d6	d7	d8
CG 61	MONTEREY	1	r2	r2	r1	r2	r2	r7	r7	r7	r7
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13	r13
DDG 53	JOHN PAUL JONES	1	r1	r1	r2	r2	r1	r7	r7	r7	r7
DDG 62	FITZGERALD	1	r4	r4	r2	r2	T	r7	r7	r7	r7
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r10	r10	r10	r10
DDG 90	CHAFEE	1	r7	r7	r2	r2	r7	r7	r7	r7	r7
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16	r16
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r10	r10	r10
CG 72	VELLA GULF	4	r7	x	x	x	r7	r7	r7	r7	r7
DDG 80	ROOSEVELT	4	r5	x	x	x	r5	r5	r5	r5	r5
DDG 100	KIDD	4	r13	x	x	x	r13	r13	r13	r13	r13
DDG 104	STERETT	4	r4	x	x	x	r4	r5	r5	r5	r5
FFG 48	VANDEGRIFT	4	r10	x	x	x	r10	r10	r10	r10	r10
FFG 52	CARR	4	r11	x	x	x	r11	r13	r13	r11	r11
SSN 718	HONOLULU	6	r7	x	x	x	x	x	r7	r7	r7
CG 58	PHILIPPINE SEA	7	r10	x	x	x	x	x	x	r10	r13
DDG 97	HALSEY	7	r11	x	x	x	x	x	x	r11	r13
FFG 47	NICHOLAS	7	r8	x	x	x	x	x	x	r8	r8

Table 31. Ship Order by Earliest Start Date (Table 1 of 2)

Ship	Name	Start Day	Start Region	d9	d10	d11	d12	d13	d14	d15
CG 61	MONTEREY	1	r2	r7	r7	r7	r2	r2	r2	r2
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13
DDG 53	JOHN PAUL JONES	1	r1	r7	r7	r7	r2	r2	r2	r2
DDG 62	FITZGERALD	1	r4	r7	r7	r7	r2	r2	r2	r2
DDG 86	SHOUP	1	r9	r12	r12	r12	r12	r12	r12	r12
DDG 90	CHAFEE	1	r7	r7	r7	r7	r2	r2	r2	r2
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	r12
CG 72	VELLA GULF	4	r7	r7	r7	r7	r2	r2	r2	r2
DDG 80	ROOSEVELT	4	r5	r5	r5	r5	r5	r5	r5	r5
DDG 100	KIDD	4	r13	r13	r13	r11	r12	r12	r12	r12
DDG 104	STERETT	4	r4	r5	r5	T	r2	r2	r2	r2
FFG 48	VANDEGRIFT	4	r10	r10	r12	r12	r12	r12	r12	r12
FFG 52	CARR	4	r11	r12	r12	r12	r12	r12	r12	r12
SSN 718	HONOLULU	6	r7	r5	r5	r8	T	r12	r12	r12
CG 58	PHILIPPINE SEA	7	r10	r13	r11	r12	r12	r12	r12	r12
DDG 97	HALSEY	7	r11	r13	T	r12	r12	r12	r12	r12
FFG 47	NICHOLAS	7	r8	r8	r8	r8	r5	r5	r5	r5

Table 32. Ship Order by Earliest Start Date (Table 2 of 2)

Ship	Name	Start Day	Start Region	d1	d2	d3	d4	d5	d6	d7	d8
CG 58	PHILIPPINE SEA	7	r10	x	x	x	x	x	x	r10	r12
DDG 97	HALSEY	7	r11	x	x	x	x	x	x	r11	r13
FFG 47	NICHOLAS	7	r8	x	x	x	x	x	x	r8	r5
SSN 718	HONOLULU	6	r7	x	x	x	x	x	r7	r7	r7
CG 72	VELLA GULF	4	r7	x	x	x	r7	r7	r7	r7	r7
DDG 80	ROOSEVELT	4	r5	x	x	x	r5	r5	r5	r5	r5
DDG 100	KIDD	4	r13	x	x	x	r13	r13	r13	r13	r13
DDG 104	STERETT	4	r4	x	x	x	r4	r2	r2	r2	r2
FFG 48	VANDEGRIFT	4	r10	x	x	x	r10	r12	r12	r12	r10
FFG 52	CARR	4	r11	x	x	x	r11	r12	r12	r12	T
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2	r2
CG 66	HUE CITY	1	r13	r13	r13	r13	r13	r13	r13	r13	r13
DDG 53	JOHN PAUL JONES	1	r1	r1	r2	r2	r2	r2	r2	r2	r2
DDG 62	FITZGERALD	1	r4	r4	r2	r2	r2	r2	r2	r2	r2
DDG 86	SHOUP	1	r9	r9	r9	r9	r9	r9	r9	T	r5
DDG 90	CHAFEE	1	r7	r7	r2	r2	r2	r2	r2	r2	r2
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16	r16
SSN 752	PASADENA	1	r12	r12	r12	r12	r12	r12	r12	r12	r10

Table 33. Ship Order by Latest Start Date (Table 1 of 2)

Ship	Name	Start Day	Start Region	d9	d10	d11	d12	d13	d14	d15
CG 58	PHILIPPINE SEA	7	r10	r11	r13	r13	r13	r13	r13	r13
DDG 97	HALSEY	7	r11	r13	r13	r13	r13	r13	r13	r13
FFG 47	NICHOLAS	7	r8	r4	r7	r7	r7	r7	r7	r7
SSN 718	HONOLULU	6	r7	r7	r7	r7	r7	r7	r7	r7
CG 72	VELLA GULF	4	r7	r7	r7	r7	r2	r2	r2	r2
DDG 80	ROOSEVELT	4	r5	r5	r5	r5	T	r2	r2	r2
DDG 100	KIDD	4	r13	r13	r13	r13	r13	r13	r13	r13
DDG 104	STERETT	4	r4	r2	r2	r2	r2	r2	r2	r2
FFG 48	VANDEGRIFT	4	r10	r9	r9	r9	r9	r9	r9	r9
FFG 52	CARR	4	r11	r13	r13	r13	r12	r12	r12	r12
CG 61	MONTEREY	1	r2	r2	r2	r2	r2	r2	r2	r2
CG 66	HUE CITY	1	r13	r13	r13	r13	r12	r12	r12	r12
DDG 53	JOHN PAUL JONES	1	r1	r2	r2	r2	r2	r2	r2	r2
DDG 62	FITZGERALD	1	r4	r2	r2	r2	r2	r2	r2	r2
DDG 86	SHOUP	1	r9	r8	r9	r9	r9	r9	r9	r9
DDG 90	CHAFEE	1	r7	r2	r2	r2	r2	r2	r2	r2
SSN 717	OLYMPIA	1	r16	r16	r16	r16	r16	r16	r16	r16
SSN 752	PASADENA	1	r12	T	r13	r12	r12	r12	r12	r12

Table 34. Ship Order by Latest Start Date (Table 2 of 2)

LIST OF REFERENCES

Department of the Navy, Office of the Chief of Naval Operations (2007). Navy Planning, NWP 5–01. Washington, DC: Government Printing Office.

Dugan, Kevin C. 2007. “Navy Mission Planner.” Master’s thesis, Naval Postgraduate School.

Joint Chiefs of Staff. 2006. *Joint Operations, Joint Publication 3–0* (Change 1, 2008). Washington DC: Government Printing Office.

Rardin, Ronald L. 2000. *Optimization in Operations Research*. Upper Saddle River, NJ: Prentice Hall.

Silva, Robert A. 2009. “Optimizing Multi-Ship, Multi-Mission Operational Planning for the Joint Force Maritime Component Commander.” Master's thesis, Naval Postgraduate School.

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